Electrical Engineering

June
1938

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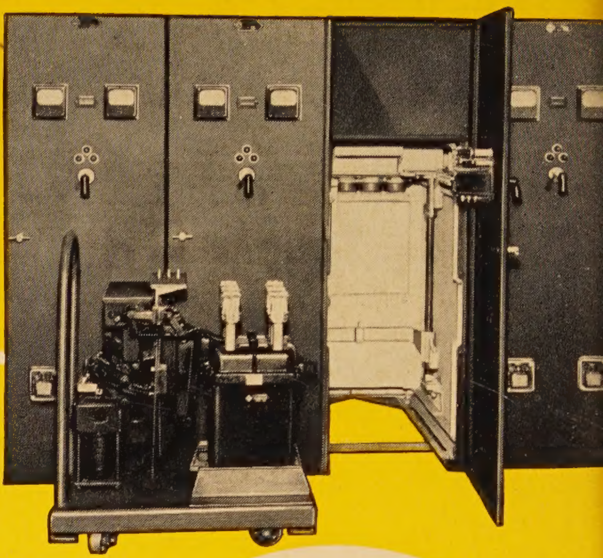

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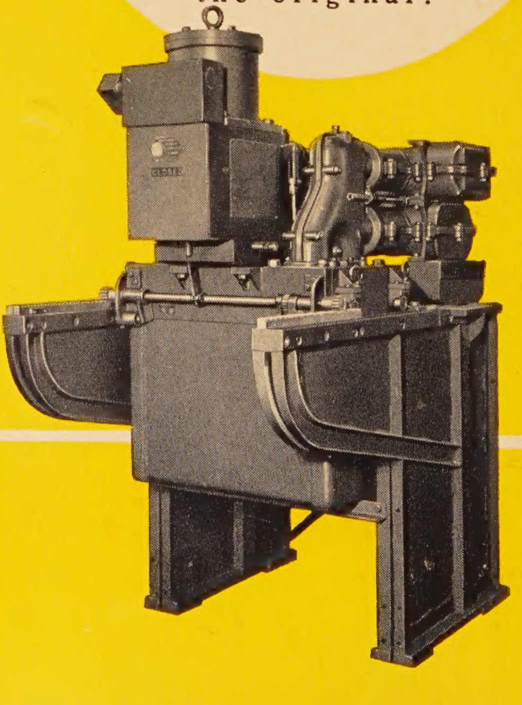

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Electrical Engineering

Registered U. S. Patent Office

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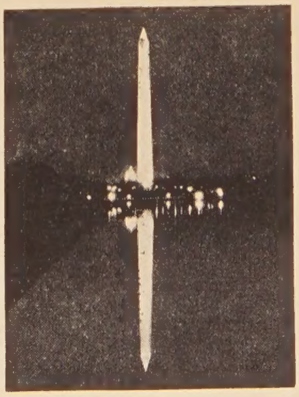
The Cover

One of the many scenes that those attending the forthcoming AIEE summer convention in Washington, D. C., may enjoy

Westinghouse Photo



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High Lights

Modern Electric Vehicles. A two-session symposium on modern electric passenger vehicles was held during the AIEE 1938 winter convention; three of the eight papers presented are published in this issue. One paper discusses the satisfactory results obtained with new street cars of the President's Conference Committee type in Pittsburgh, Pa. (*Transactions pages 315–17*). A comparison between busses having mechanical drives and gas-electric drives for a transportation system in Philadelphia, Pa., faced with the necessity of replacing much of its equipment, is reported in the second paper; tests showed greater fuel consumption for gas-electric drive, but also higher schedule speed and lower maintenance (*Transactions pages 318–23*). How a transportation company in Chicago, Ill., is attempting to satisfy the demands of its customers for new style, more power, greater comfort, and higher speed is told in the third paper (*Transactions pages 324–7*).

Electronic Speed Control. Two papers in this issue describe methods of using electronic devices for controlling the speed of electric motors. One paper (*Transactions pages 343–52*) outlines three methods of controlling the speed of a motor operating from an a-c power supply. For controlling the speed of d-c motors, the thyratron offers full control and quickness of response (*Transactions pages 335–42*).

Fluorescent Lamps. Heretofore, colored light has been obtained primarily from incandescent lamps by means of some special filtering material, at relatively low efficiency. A recently introduced low-voltage fluorescent lamp is capable of producing colored light, as well as a good imitation of daylight, at efficiencies much greater than those associated with incandescent lighting (*pages 245–8*).

Transmission for Television. If the art of television should follow a path similar to that of radiobroadcasting, some means for connecting stations will be required that can transmit a band width of several megacycles without appreciable distortion. Recent experiments have shown that coaxial cables, developed for telephone use, may be adapted to fulfill the requirements (*pages 249–56*).

Today's Opportunity for the Young Engineer. The young engineer graduating from college today faces a difficult situation. By cultivating a practical point of view toward it, however, he may gain experience at the very outset that will assist him in solving problems likely to recur again and again throughout his entire professional career (*pages 256–8*).

Petersen Coils. Application of a Petersen coil to a transmission line traversing mountainous country and exposed to lightning is reported to have reduced the number of tripouts caused by lightning. The coil was adjusted or tuned with the system in two ways, and staged tests were made of the arcing time at faults (*Transactions pages 295–302*).

Lightning Currents. Study of three-year records of several companies relative to lightning discharge currents through distribution lightning arresters shows that 50 per cent of the currents may be at least as great as 1,300 amperes; circuit rating seems to have no definite effect on discharge currents (*Transactions pages 307–12*).

Summer Convention. Details of the business and technical sessions of the AIEE 1938 summer convention being held June 20–24 in Washington, D. C., have been completed. The program includes ten conference sessions, and the annual business meeting and conference of officers, delegates, and members (*pages 259–61*).

Electricity in Medicine. Electricity in the practice of medicine may be either an esoteric instrument of the quack or a useful tool in the hands of a competent physician. Many of the legitimate electromedical devices, which are based upon sound scientific principles, may be interesting to electrical engineers (*pages 237–44*).

Thyratron Lighting Control. Among the many control applications of the thyratron tube is the control of lighting intensity, particularly in theaters. Some of the new equipment, new systems, and new theatrical practices made possible by the use of the thyratron are described in this issue (*Transactions pages 328–34*).

Pacific Coast Convention. Arrangements for the AIEE 1938 Pacific Coast convention are nearing completion. The dates, August 9–12, are particularly attractive to those wishing to make combined vacation-convention trips (*pages 260–1*).

Section and Branch Activities. During the year ending April 30, 1938, 624 meetings of AIEE Sections and 1,334 meetings of Student Branches were held; three new Sections and one new Branch were organized (*pages 263–6*).

Coming Soon. Among articles and papers now undergoing preparation for publication in early issues, are the following: an article on the role of the library in engineering education and research, by H. W. Craver; an article discussing the engineer and his relation to current trends in economic thought, both in the United States and in other countries, by Past President F. B. Jewett; an article presenting a graphical method of multiplying and dividing complex quantities, by E. C. Goodale (A'27); an article philosophically discussing our scientific era from the historical point of view, by Alfred Still (F'14); a paper describing a high-speed circuit breaker for railway use, by W. F. Skeats (M'36); a motion-picture study of traveling waves on transmission lines, by L. F. Woodruff (M'33); a paper presenting the results of a calculating-board study of the recovery-voltage characteristics of transmission systems, by R. D. Evans (M'26) and A. C. Monteith (A'25); and a paper describing a stabilized vacuum-tube amplifier devised for use in the measurement and instrument system of an a-c network analyzer, by H. A. Thompson (A'37).

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Communication

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A New Single-Channel Carrier Telephone System—Fisher, Almquist, and Mills 356
A System of Electric Remote-Control Accounting—Woodruff 357

Transportation

The PCC Street Car—Hirshfeld 355

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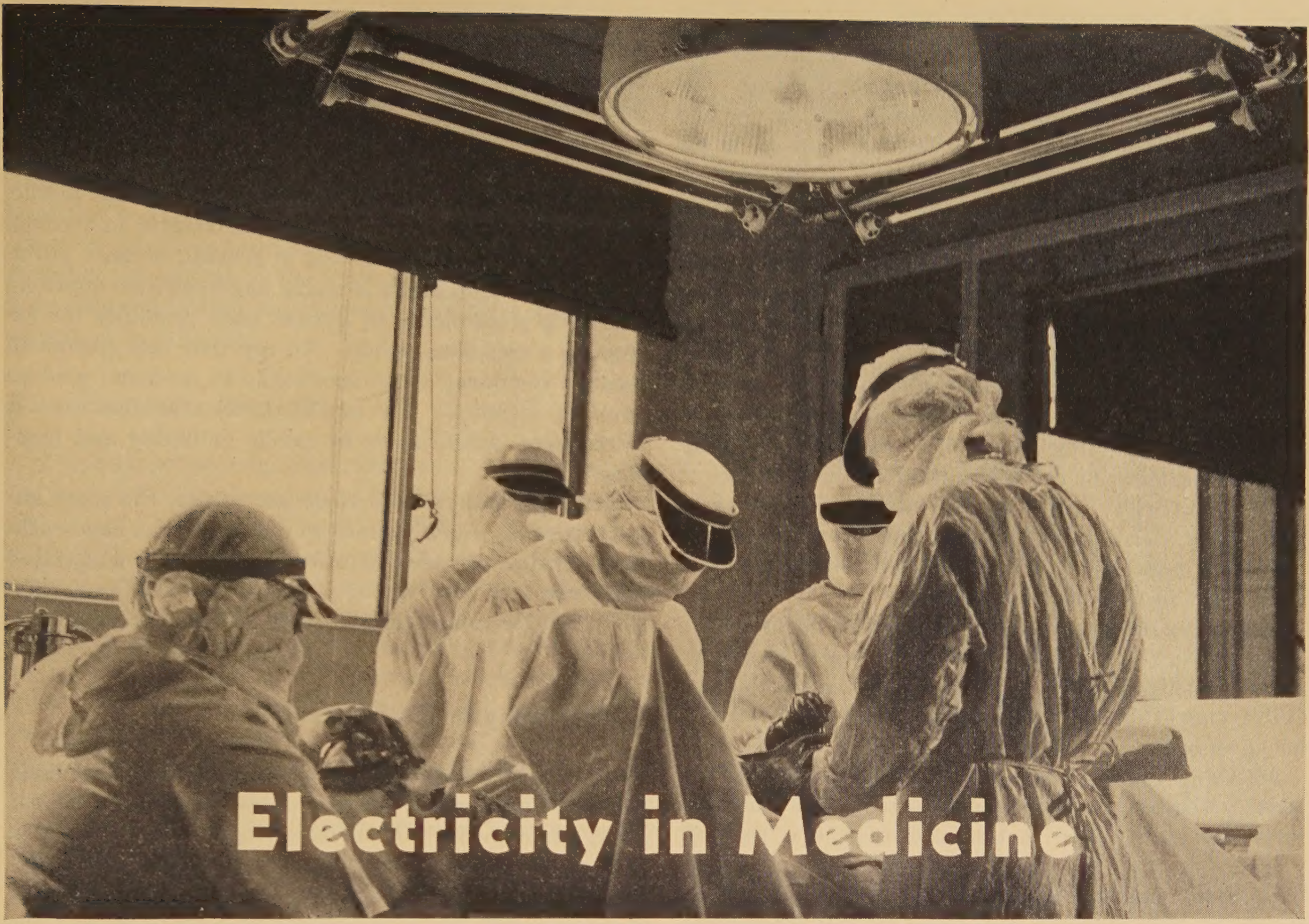

Electricity in Medicine

As long ago as 1882 D'Arsonval predicted that electricity would be used widely in the treatment of disease. Today that prediction has been fulfilled—indeed, exceeded—because electricity now plays a highly important part not only in the treatment of disease but also in its detection and diagnosis. A few of the manifold electromedical applications are described here.

By R. E. WILLIAMS
ASSOCIATE AIEE

PROBABLY medicine as a profession antedates all other scientific professions of which there is any record. Instinctive in man is the urge to administer aid to a fallen comrade, or to secure relief from illness or plague. Egyptologists and Orientalists have reported definite historical evidence of the practice of medicine in ancient Egypt, China, and other oriental nations, but imagination need not be overtaxed to recognize a crude attempt at the practice of medicine among even the remotest of prehistoric races. Indeed, wherever the light of knowledge and education has not managed to infiltrate the gloom of centuries, remnants of primeval races still tolerate the tom-tom-beating medicine man, the conjurer, and the herb doctor.

Many centuries later the medical practitioner began to look to science—basic chemistry and physics—for assistance in his attack upon the vagaries and superstitions surrounding the theories of human maladies. In the meantime electricity, in contradistinction to medicine, had had its beginnings as a science; yet for more than 1,000 years, through the Dark Ages and even beyond the Renaissance in Europe, the theories of electricity, like medicine, were so shrouded in occultism, charlatanry, and alchemy that probably not until 1748 did the science of electricity find a definite identification with the profession of medicine. In that year, according to de La Rive,[1] the therapeutic applications of electricity were first entertained by Jallabert (or Jalabert), who submitted invalids to electrical treatment by drawing sparks from their bodies. He thought he discovered that electrization stimulated the circulation of blood, that it was capable of awakening dormant sensation or restoring to usefulness a paralyzed organ, and that it produced involuntary convulsive movements. He is said to have ameliorated by the applications of electricity the inconvenience of a man whose arm was paralyzed. A detailed account of this experiment by Jallabert was read by Teske[2] before the Royal Society in London in 1759.

Galvani[3] contemporaneously carried on important investigations in physiological electricity, but his interests were mostly hypothetical, and the application of his discoveries

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R. E. WILLIAMS is a member of the Institute's publication staff. The author acknowledges the assistance of Doctor J. M. Carlisle, Westfield, N. J., and the generous co-operation of Doctor H. A. Carter, secretary of the council on physical therapy, American Medical Association.

[1] For all numbered references, see list at end of article.

was left to Humboldt, Aldini (Galvani's nephew and pupil), and others. Galvani first demonstrated the existence of animal electricity by means of a frog. He made an electrical connection between the nerves and muscles of a frog and observed an electric current in the connecting link; but unfortunately the interconnection was bimetallic, and Volta contested Galvani's findings on the premise that the current was produced by a thermocouple action instead of an internal generation of electricity. Galvani then used a homogeneous metal to connect the muscles and nerves of the frog, and obtained similar results; whereupon a long discussion was precipitated between the two men and their respective partisans, concerning the cause of the muscular contractions experienced by the frog during the original experiment. Galvani persisted in the assumption of the existence of animal electricity; Volta sought with equal tenacity to prove that the current could be produced by contact potentials between any two dissimilar substances, however slight the dissimilarity might be.

Both sides of the argument, which grew bitter toward the end, were conducted with almost equal ingenuity, but eventually the ideas of Volta gained credence among the savants of the day and predominated over the logic of his adversary.

Such were the beginnings of contiguity between the two broad sciences of electricity and medicine. The road they have traveled together has been a tortuous one, for with propriety entirely becoming the profession, physicians have been reluctant to accept new methods until the merits of such methods have been proved irrefutably. The use of electricity in medicine has been somewhat handicapped moreover by a lack of general understanding of its nature, and physicians have been concerned necessarily with the possible adverse psychological effects produced in patients by the use of electrical devices in either the diagnosis or treatment of diseases.

Today the barriers of antipathy and misunderstanding are being set aside, and electricity is becoming a valuable ally of the physician in his never-ending crusade against the maladies that beset the human body. Electricity is proving its merit. Medical practitioners and investigators have not often acepted strange, untried electromedical equipment with open arms; they have rejected it time after time, forced designers to improve it, and have used it only after it has been found to offer concrete practical advantages over more conventional equipment. Electrical devices probably never will revolutionize the science of medicine, but there are many interesting and successful applications of electricity in medicine, and a few of the more important ones are described in the following paragraphs.

Electricity in Diagnosis

Dozens of different kinds of electrodiagnostic contrivances have been manufactured, sold, used; and many have been cast aside during the last 25 years. Some of them have been worthless but harmless; others have been instruments of quackery; a few have survived all the scientific and ethical demands of the medical profession, and are in general use today. Occasionally irresponsible manufacturers have attempted to project worthless "gadgets" into medical science, or to circumvent legitimate medical practitioners by selling expensive, useless, perhaps harmful, spurious electromedical apparatus to the public. Such practices have been definite deterrents to medical acceptance of electrical devices in general, because physicians have maintained a laudable aloofness from anything bearing a resemblance to devices used primarily for exploiting a credulous public. To say that fads prevail in medical treatment is not necessarily to condemn modern curative technique, for much of the "modishness" is forced upon practitioners by public gullibility and ignorance.

Although undoubtedly there are others, the most important of the electrical aids to diagnosis that have withstood critical scientific scrutiny and have demonstrated their own merit over a long period of time are (1) X rays, (2) the electrocardiograph, and (3) the incandescent lamp.

Radiography in Diagnosis

No lengthy exposition of the use of X rays as a diagnostic medium is necessary, for the importance of the X-ray department in the modern hospital and its function in diagnosis are fairly generally understood. X-ray equipment is indispensable in both the diagnosis and treatment of disease, but the improvement in apparatus and the technique of its use has been so rapid that few general practitioners find it profitable to keep either their knowledge or equipment fully up to date. As a result, X-ray technicians have begun to establish a specialized field in medicine. About one-fourth of all practicing physicians in the United States own some X-ray equipment, but there are more than 1,000 that devote their entire time to X-ray research and treatment.

The X rays of most interest, and most useful to medical science, are those with wave lengths of from 0.1 to 1 angstrom unit, although both longer and shorter waves have been produced, and probably may be found useful.[4] Several hospitals in the United States now are using X rays produced at 1,000,000 volts or more, but such "hard" radiations have found little use in diagnosis.

The layman is familiar with radiographs of bony structures for the detection of fractures or malformations, but this is only a beginning of the nicely refined technique of radiography. Bones, teeth, foreign bodies, and any dense or calcareous parts immediately are thrown into shadow relief upon application of the radiations. This is simple—but a whole science has evolved from the attempt to outline some of the soft tissues and organs of the body. By administering either orally or by injection a suspension of barium sulphate, which is highly opaque to X rays but is not absorbed by the body, the alimentary canal may be examined. The precipitate of barium salt lines the canal and therefore outlines the tract on the X-ray film. Other soft organs may be "isolated" for purposes of X-ray diagnosis by injections of iodized oil and other chemical substances that are concentrated specifically in the organ under observation.

Diagnosis of conditions in pregnancy is a relatively new application of radiography. Frowned upon at first by superstitious or apprehensive patients and conservative physicians, it is believed now to be perfectly safe in the hands of a competent roentgenologist. It is particularly useful in detecting multiple pregnancy and malformations in either the patient or the fetus, so that the obstetrician may take suitable precautions early enough to avoid complications in delivery.

The Electrocardiograph

The electrocardiograph is an instrument used for detecting and recording the minute electrical variations within the heart. According to existing physiological concepts, activity in all living tissue is associated with an electrical change. The active part of the tissue acquires a negative potential with respect to the inactive part, and a current will tend to flow through an external circuit from the inactive part to the active, if suitable electrodes are applied. Incidently, Galvani enunciated the essence of this theory during his work on electrophysiology already mentioned. Activity in muscle is associated with surprisingly large changes of potential—20 millivolts or more—and in the heart, which fundamentally is no more than a mass of specialized muscular tissue arranged so that the organ functions as a pump, the activity is rhythmic. Accordingly, there is a corresponding rhythmic, periodic wave of potential difference between any two points on the surface of the heart.

The tissues surrounding the heart are fairly good conductors of electricity; consequently, much of the potential difference between the two points on the heart's surface disappears. If electrodes are applied to the hands or arms, the rhythmic differences of potential corresponding to the activity of the heart may be detected, however, and usually have crest values of one millivolt or more.

That the action of the heart is accompanied by electrical changes has been known since 1856, when Kölliker and Muller demonstrated by physiological experiment that the beat of the isolated heart of a frog was accompanied by electrical changes. Waller, an English physiologist, demonstrated in 1887 that the heart current could be made to pass through a galvanometer and cause it to deflect, but little significance was attached to the discovery at that time.

In 1903 Einthoven designed a string galvanometer of sufficient delicacy to respond to the rapidly varying electrical changes from the heart, and following the publication of his clinical studies several years later, the clinical use of the electrocardiograph became more widespread until today it is an important adjunct in not only the diagnosis but also the prognosis of heart conditions and diseases. Much of Einthoven's technique is still used as standard clinical practice today, principally because his work was thorough and rational, and because some sort of standardized practice is necessary in order that the work of various cardiologists may be directly comparable. The three standard connections to the patient, or "leads," used universally just as Einthoven prescribed them, are made in such a way that the first record delineates the voltages across the base of the heart; the second shows voltages between the base and apex of the heart; and the third describes electrical changes chiefly in the left ventricle.

Superficially, there are three kinds of electrocardiographs: (1) the string-galvanometer type; (2) the amplifier type; and (3) the cathode-ray type.

The string-galvanometer electrocardiograph, which essentially is only a variety of recording galvanometer, has been used in hospitals and special clinics for several years, and has given reasonably accurate, dependable results; nevertheless, it has many unsatisfactory characteristics that likely will cause it to be displaced eventually by the other types of equipment, which are more convenient. The other two kinds of electrocardiographs are fundamentally similar to the vibrator and cathode-ray oscillographs used in electrical engineering, the only notable departure being in sensitivity. For example, Reid and Caldwell,[5] in studying special problems have used an amplifier electrocardiograph of such high sensitivity that strips of sensitized paper five inches wide are necessary to record the high amplitudes of the amplified heart waves.

Details of electrocardiographic circuits and operating technique are interesting, perhaps in themselves worthy of separate description. But an exposition so extensive cannot be told in a few words; besides, there is little point in reiterating a story already well told elsewhere.[5–10] For those interested in the significance and interpretation of electrocardiograms the descriptive works of Wiggers[7] and Wilson[11] are recommended.

The Incandescent Lamp in Diagnosis

Physicians have found no new or startling uses for incandescent lamps, which have the same use in medical diagnosis as in every man's home—to supply light in dark places. In examining the passages of the respiratory and digestive systems the incandescent lamp is to be found in daily use in any well-regulated clinic. The forms of the lamps may be as unfamiliar as the names of the technique for which they are used, but the actual use seldom departs from this fundamental purpose of lighting dark cavities of the body. In rare instances incandescent lamps are used for controlled local heating.

Aside from the unusual shapes and sizes of the envelopes, medical incandescent lamps are not much different from the prosaic article now purchasable for a few cents at the corner drug store.

Relation of Body Impedance to Disease

Many investigators have attempted to explain the action of a human body included in an electric circuit. Its electrical characteristics have been described by means of equivalent circuits, and determined quantitatively by measurement; yet no correlation between disease and electrical characteristics of the body has been rationalized sufficiently to become generally valuable in diagnosis. As long ago as 1888 Vigouroux observed that ostensibly the d-c resistance of the human body changes during diseases of the thyroid gland, but later experiments[20] failed to corroborate that hypothesis. Strangely, although failing to confirm Vigouroux's correlation of d-c resistance and irregularities of the thyroid gland, Brazier, among others, has found a rather definite relationship between body impedance (or really what he termed "impedance angle," the ratio of reactance to impedance) and the basal metabolic rate.

Since the determination of the basal metabolic rate is a routine aid to the diagnosis of thyrotoxicosis, the measurement of body power factor logically could be applied as a diagnostic test for diseases of the thyroid gland. The basal metabolic rate is a measure of the energy output or heat production of an individual in state of complete mental and physical rest. It is measured as the calorie output per square meter per unit of time, and is subject to enormous errors; therefore, the method of diagnosis by means of alternating current may become highly significant in clinical practice. At present the method still is a research implement. It has been used experimentally in England, and at Harvard University and The Johns Hopkins University in the United States.

Electricity in Therapy and Surgery

Possibly because of much publicity, the layman is more aware of the glamorous part played by electricity in the cure of disease than of the equally important processes of electrodiagnosis. For example, most people have been informed that X rays are being employed, perhaps with some small degree of success, to wage war against that dread foe of mankind known as cancer, for only through widespread public education can the medical profession hope to combat such an insidious malady. It is cured with least difficulty if detected in the simple unobtrusive forms in which it frequently first manifests itself. This is a legitimate use of medical publicity, yet not all electromedical processes have been publicized so worthily. Many formidable-looking machines without any scientific justification, but apparently with much psychological and "box office" appeal, have been used for years by quacks and charlatans, the modern versions of the medieval mystics. One of these electrical gadgets supposedly was based upon a theory that every disease causes the body to radiate electrical energy at some specific frequency peculiar to that disease. The same machine diagnosed and likewise treated all diseases, each malady having its own colored light on the front of an impressive control panel. As the specific frequency of the patient was discovered, the proper colored lamp flashed, thus "informing" the operator of an actually predetermined treatment. The treatment, the same for tonsilitis or gall stones, consisted of some sort of electric shock that never failed to *impress* the patient; and sometimes it effected a complete cure—at least psychologically. Most ethical physicians merely looked askance at this remarkable machine, but a few crusaders succeeded in making it look so ridiculous that it retired from the scene hastily and confusedly. The name of this miracle machine is known to most physicians, and many volumes could be written about equally famous, or infamous, devices employed by pseudomedical cults of the present and the past; however, that is a separate chapter in medical history and is of no interest here, except to show why many conservative medical practitioners are inclined to be skeptical of unproved electromedical equipment, and why the actual development and application of electromedical equipment proceeds so slowly.

The legitimate and accepted division of medical treatment known as physical therapy may be divided into five main branches:

1. Light therapy, the treatment of disease by means of "light" rays.
2. Heat therapy, employing various types of heating devices.
3. Electrotherapy, using electricity.
4. Hydrotherapy, the employment of various water applications.
5. Mechanotherapy, treatment by massage, corrective exercises, and mechanical devices.

Light therapy includes treatment by ultraviolet and infrared radiations; heat therapy includes stimulation of artificial fever by means of high-frequency radio emissions; electrotherapy, in its restricted medical sense, is the treatment of disease by means of electric or diathermy current used to produce deep local or general heating effects. Hydrotherapy is commonplace: As a stimulant, cold water is dashed into the face of a fainting person; as a sedative, a bath at 100 degrees Fahrenheit is prescribed; as an invigorator the cold shower is well known.

Obviously electricity is indispensable in light therapy, heat therapy, and electrotherapy, and may be important in the other branches of physical therapy. But this is only a beginning of the therapeutic applications of electricity. Most important of the other uses are: radiotherapy, the treatment of disease by means of radium and X rays; and electrosurgery, which of course is a corrective technique being considered arbitrarily among the therapeutic applications.

Light Therapy

"Light therapy may be defined as the treatment of diseases by means of light rays (particularly invisible light rays)."[12] The definition of light therapy given by the council on physical therapy of the American Medical Association is: "a limited term used by some physicians to designate the therapeutic application of radiation in the visible spectrum: some include also ultraviolet radiation." Although this latter definition is more precise scientifically, it is not correct practically, because in general the term "light therapy" is used rather loosely in discussing all types of radiation; that is, ultraviolet, visible, and infrared.

As radiant energy is absorbed by the tissue cells it produces a complex variety of physical, chemical, and biological reactions. From the standpoint of physical therapy, radiant energy is classified as either photothermal or photochemical radiation.[13] Photothermal radiations, comprising infrared and visible radiations, penetrate subcutaneous tissues, heat the blood, accelerate vital reactions, act instantaneously; they produce a burning sensation or immediate burn, if their intensity is too great.

Photochemical radiation, or ultraviolet radiation, penetrates the skin only to a depth of a fraction of a millimeter; it is absorbed by protoplasm, and this absorption causes physical and biological changes that manifest themselves only several hours after exposure. Thermal radiations are employed usually for immediate local action, but photochemical radiations are used for their subsequent effect on the general organism.

The medical profession is divided in opinion regarding the therapeutic expediency of these radiations. Some contend that ultraviolet applications are useful only as a substitute for heliotherapy (treatment of disease by exposure to the sun's rays); nevertheless, in many instances the use of artificial ultraviolet generators ordinarily is more convenient than heliotherapy, and a desired dosage may be administered more quickly and accurately. Furthermore, specific wave bands may be filtered from the output of the clinical ultraviolet generator for special long- or short-wave radiations, although there is little clinical evidence that the effect of the short-wave ultraviolet radiations physiologically is any different from the effect of the long-wave ultraviolet, except that the long waves have slightly greater penetrating power.

Ultraviolet radiations applied locally may be useful in their bactericidal action. Almost all bacteria may be killed by sunlight or the radiant energy emitted by artificial sources, but there is much variation in the rapidity with which they are destroyed. A bactericidal action is exerted by all radiations having wave lengths between 3,000 and 2,500 angstrom units, although there is a definite characteristic curve of bactericidal effectiveness for different bacteria; for instance, emissions at 2,650 angstrom units are said to be most effective for colon bacilli.

As radiant energy at wave lengths shorter than 4,500 angstrom units does not penetrate the skin, destruction of germs in the deep sections of the skin is impossible, and the direct bactericidal action of ultraviolet is most useful in treating infections located on the surface of the body.

Infrared radiation should not be assumed to have any extraordinary therapeutic effect. It is merely a convenient method of localized heating of some part of the body. Both luminous and nonluminous heat radiations produce marked hyperemia (abnormal localized accumulation of blood), tissue relaxation, and relief of pain in the irradiated area. These effects assist in the resorption of products of wounds and inflammatory reaction and aid the natural forces of defense and restoration.

The advantages of infrared irradiation over the more conventional method of conductive heating are that its action is effective to a much greater depth; there is no pressure over the parts treated; and the parts may be kept under continuous observation, so that signs of excessive heating may be discovered at once. In all sources of ultraviolet radiation the proportion and intensity of the various wave lengths varies widely; moreover, variations in styles of reflectors, applicators, current, voltage, and distance between electrodes affect the intensity of the radiations, so that different radiations may be obtained from the same source merely by changing the controlling conditions. Because of these variables, the council on physical therapy of the American Medical Association has established a standard, based upon the erythemal (broadly, "sunburning") effect, for judging the effectiveness of ultraviolet sources. Since the emission line of the mercury-arc lamp at 2,967 angstrom units has the greatest erythemal effect, this line has been selected as the standard of evaluating all other sources, and an energy concentration of 20 microwatts per square centimeter at a distance of two feet from the front edge of the reflector, at this standard wave length, is known as the erythemal unit (E.U.) of dosage.

Readers interested in the apparatus used for light therapy should consult an article by Laurens,[14] who has written definitively concerning the various types of radiant-energy sources, including a résumé of the factors involved in the selection of the proper variety for a specific application, and Coblentz[15] has described the physical characteristics of the radiators in a manner far more adequate than is possible here.

X-Ray Therapy

Each variety of cell in the body is specifically sensitive to roentgen rays or the radiations emanating from radium. Certain cells are extremely sensitive and are destroyed or injured by small doses; other varieties are resistant and can tolerate relatively large doses with apparent impunity.[16] On this simple premise hinges a field of therapeutic treatment scarcely touched by medical research, and probably little understood. On the basis of many experiments, radiologists have determined that the radiosensitiveness of cells depends largely upon their rate of metabolism; in other words, upon the natural life cycle of the cells. Logically, an abnormal cell probably does not have the same life cycle as a normal or healthy one, so that by careful selection of frequencies and dosages, the roentgenologist can concentrate upon unhealthy cells and deter or destroy their growth with only small detriment to surrounding tissues, because of their differences in sensitiveness.

The absorption of the rays in the human body is governed by definite physical laws, and the proper use of X rays for therapy requires exact knowledge of the quality, or wave-length distribution of the rays, and of the quantity or dose. If the proper wave length is known, the voltage to be applied to the tube may be computed approximately from the equation of Duane and Hunt[17]

$$V = \frac{12.35}{\lambda}$$

in which V is the potential difference in kilovolts and λ is the wave length in angstrom units.

Skin diseases ordinarily are treated with "soft" rays, or so-called "grenz" rays, because only the long-wave rays are absorbed by the skin. Short-wave rays pass through the skin with little effect, but to treat an internal tumor such radiations are necessary. If the generation of X rays with only a single wave length under given conditions were possible, the entire technique of X-ray therapy would be greatly simplified, but the radiations generated in an X-ray tube are heterogeneous and contain various wave lengths, each with a different absorbability in the body and a different therapeutic effect. Nevertheless, the heterogeneous beam has an "effective" wave length that is characteristic of the radiations always generated under the same conditions. In order to screen out the softer rays, better to control the known characteristics of the beam and make it more homogeneous, metallic filters sometimes are used.

Exposure to X rays may be followed by loss of appetite, nausea, and vomiting. The intensity of such reaction depends upon the part of the body exposed, the area of the surface, and upon the ease with which the digestive equilibrium of the patient may be disturbed. Prolonged or continual exposure to the radiations may cause sterility, annoying, painful burns that heal slowly, and other disorders. Consequently, the dosage of X rays must be controlled accurately to obtain the desired result; in 1928 an international unit of dosage, the roentgen unit or *r*, based upon the ionizing power of the rays upon air, was adopted by roentgenologists. Treatments therefore are specified in so many *r* units per minute.

About 1920 radiotherapy entered a new phase, and has continued to expand in the manner then adopted. Previous experience had shown that in the treatment of resistant tumorous growths, especially those residing in the deep portions of the chest or abdomen, the rays available at that time were not particularly effective. This was thought to be attributable to the inability of the rays to penetrate the body sufficiently to reach the malignant growths; therefore, a clamor for more penetrating rays arose among the roentgenologists, and tube designers and manufacturers of X-ray equipment proceeded to satisfy the demand by producing apparatus operating at voltages of from 200,000 to 300,000. Such generators enabled the therapeutic radiologist to deliver to deeper parts of the body a much larger dosage of the rays, and as a result certain tumors, previously not responsive to radiology, became somewhat more corrigible.

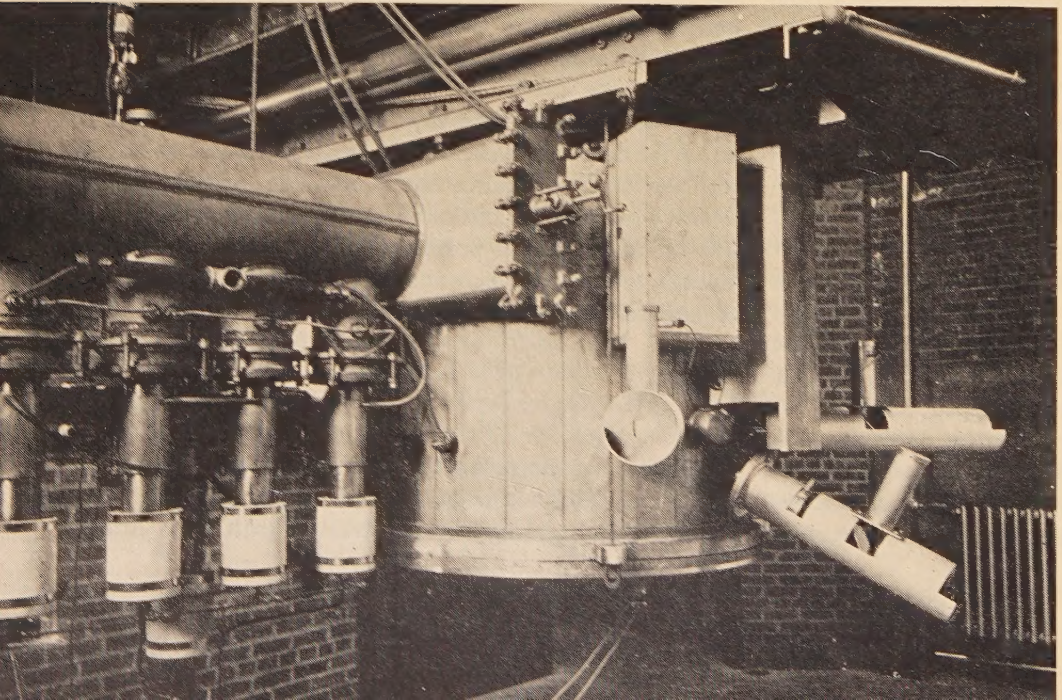
In spite of these improvements, certain tumors were not influenced by any variation, and this led to a demand for still more penetrating rays. Another reason for the demand is that the high cost of radium prevented many institutions and private practitioners from using that element for external radiation at a distance. Only a few institutions in the world have a sufficient quantity of radium to employ it in this way; as a result, since 1930 several X-ray machines capable of operating at from 500 to 1,000 kilovolts have been constructed. Radiations generated at such high voltages are extremely penetrating and, although they do not correspond exactly to the gamma radiations of radium, they produce a somewhat similar result. One of the largest machines of this type is used by the Institute of Cancer Research of Columbia University almost exclusively in irradiating cancerous growths, and is situated in the Presbyterian Hospital in New York City. Apparatus operating at comparable voltages is in operation at the Huntington Memorial Hospital of the Harvard Medical School at Boston, Mass.

Although such high-voltage equipment is desirable and advantageous, it cannot replace radium or therapeutic apparatus of lower voltage because each has a definite specific use and value in medicine, and is indispensable. It is still in the experimental period of development, has only highly specialized applications at present, but possibly may become a potent weapon in the war against cancer.

Electrotherapy

As Jallabert found, the conduction of current through the body effects some profound reactions, which may be beneficial in the treatment of disease. Jallabert probably did not know why electric currents mitigated the suffering in the bodies of his patients, but today the physiological

Photo courtesy Doctor Francis Carter Wood



This $30,000 therapeutic X-ray generator, which is operated experimentally by the Institute of Cancer Research of Columbia University in New York City, is capable of producing radiations at 1,250 kv, but normally operates at 900 or 1,000 kv. Radiations are projected through lead-covered stainless-steel tubes, which may be seen at the right in the photograph, and may be aimed accurately at cancerous growths. Four patients may be treated simultaneously and therapeutic actions of electricity are known precisely to be attributable to chemical and physical changes that it produces in the tissues.

For some years high-frequency currents were used empirically in medicine, without much knowledge of the reasons for their therapeutic effects, but the physiological and therapeutic results now are believed to be entirely dependent upon the generation of heat within the tissues. Just as some electrical energy is consumed in overcoming the resistance of ordinary conductors, so the body tissues consume energy, and the temperature rise may be many degrees above normal. The heat generated by high-frequency current is distributed along the path traversed, so that the deep tissues may be heated as well as the superficial tissues, and for this reason such currents are called "diathermy" currents.

METHODS OF TREATMENT BY DIATHERMY

So manifold and complex are the uses of diathermy and closely related practices that volumes could be, and have been, written on this subject alone. Arbitrarily the whole field of diathermy may be divided into four parts: (1) general diathermy, (2) autocondensation, (3) hyperpyrexia by diathermy, and (4) electrosurgery. The fourth may not be, by definition, a class of diathermy treatment, but is closely related to the others so far as the physical characteristics of the process are concerned, and is most conveniently considered with the others.

General diathermy denotes the use of high-frequency current for general heating effects on the body, by the employment of a large electrode surface in direct contact with the skin. Autocondensation is a modification of this method, in which a dielectric is interposed between one electrode and the skin; in other words, the body is made a part of a capacitor. Both methods have been used for years, principally for their mild stimulating effect on body metabolism, although autocondensation was popular at one time for the treatment of high blood pressure. The slight rise in body temperature caused by their use was at first considered to be incidental, and the therapeutic effects of the treatments were attributed to specific influences of the high-frequency currents rather than to the elevation of body temperature.

As a result of more recent investigations in fever production (hyperpyrexia), however, the beneficial effects of the treatments have been acknowledged to be produced by the heating, and diathermy apparatus of larger capacity has been produced for the specialized technique of fever induction. Moreover, the generation of therapeutic fever in a capacitive field by means of high-frequency radiations in the radio spectrum has created a need for apparatus still more powerful, and to operate at still higher frequencies.

General Diathermy. The object of general diathermy is to pass through large electrodes connected to the body a diathermy current of sufficient density to influence general blood circulation and body metabolism. As practiced with apparatus supplying only a small power output, this method produces a temperature rise of only one or two degrees Fahrenheit above normal. With the patient connected to an average diathermy machine by means of large electrodes covering perhaps 100 square inches of skin surface, the diathermy current through the electrodes may be as much as three amperes. After half an hour of such treatment the body temperature usually does not exceed 100 degrees Fahrenheit.

Autocondensation. The physical effect of an autocondensation treatment is to produce local heating of the parts of the body to which the electrodes are connected, as well as to produce general heating of the body as in general diathermy. Ordinarily one or two metal cylinders or plates are applied by direct contact to the palms of the hands, forearms, soles of the feet, or chest, and connected to one output terminal of the diathermy apparatus. A very large electrode, separated from the body by an interposing pad of insulating material, is connected to the other terminal, thus making the patient a part of a capacitor in an oscillatory high-frequency circuit.

The current dosage normally varies from 0.5 to 1.25 amperes applied for 10 or 15 minutes. In the early days of high-frequency therapy a method of autoconduction was practiced, and still is used by some clinicians in Europe. A variant of autocondensation, it consisted of placing the patient inside a solenoid and electromagnetically inducing the high-frequency current in his body.

Hyperpyrexia by Diathermy. Fever production is said to aid the defense and protective mechanisms of the body in some chronic diseases, and is especially helpful in the treatment of gonorrhea, both acute and chronic, because the bacillus of that disease is easily killed by slight increases in temperature. In the treatment of syphilis of the spinal cord there is a race for supremacy between the electrical methods of fever production and the injection of the malaria organism, both of which are capable of producing high fever. Both methods have given favorable results, but neither is sure to bring about any permanent benefit. Electrically induced fever as a curative measure has not received universal approval among medical men, and many prefer to accomplish a similar result by the mere application of heat in an oven; at any rate, further careful study and much practical experience in fever therapy seem to be needed before the best method and the scope of artificial fever production may be determined conclusively. The advantages of electrical fever induction over most of the other methods are said to be the accuracy with which the reaction of the patient may be observed and controlled; the constant availability of the therapeutic agency; and sterility, because the procedure does not introduce toxic substances.

To bring about hyperpyrexia by diathermy the current must be sufficient to produce more heat than is lost by radiation, and some suitable means of insulation is provided to keep the radiation losses as low as possible. At a frequency of 1,000 kilocycles per second the ordinary electrode current requirement is about four or five amperes, which will produce temperatures up to about 107 degrees Fahrenheit without harm.

A few years ago a new method of artificial fever induction was discovered accidentally when persons working near a powerful high-frequency radio transmitter became overheated and complained of headaches. The overheating was found to be caused by the high-frequency radiations of the transmitter. A special apparatus for producing the same effect, later described by Whitney,[19] was called the "radiotherm," and the method of hyperpyrexia by high-frequency radio waves became known as radiothermy.

Electrosurgery. Any person who has allowed any part of his body to touch a conductor carrying radio-frequency current in a high-voltage circuit needs no description of the theory of electrosurgery, for by practical experience he became acquainted with an excellent potential electrosurgical instrument.

The principal action of all electrosurgical methods is an intense concentration of current under a small active electrode, resulting in a destructive heating effect that leads to instantaneous coagulation of the albumin of the tissues. The extent and form of destruction varies with the type of current and the method of application. In electrocautery—the employment of metal tips or wires heated by ordinary lighting current—the destruction of tissues is superficial and impermanent, and the metal tips cannot be kept at a uniform temperature. The modern high-frequency electrosurgical operating instrument is merely a scalpel or needle connected to a single (ungrounded) terminal of a high-frequency oscillator circuit. Although the instrument remains cool throughout the surgical procedure, a searing heat is developed in the tissues themselves, and is under perfect control of the operator. Electrosurgery, offering complete sterilization of all tissues through which the instrument passes, as well as a remarkable reduction in capillary hemorrhage, has come to fill a definite role in both major and minor surgery, and has made possible some important advances in general surgical technique. In particular the practice of brain surgery has been given an important impetus by the use of electrosurgical devices. Ordinarily, excessive bleeding and the consequent possibility of postoperative shock make brain surgery a hazardous undertaking strictly within the province of a very few specialists. Possibly through the use of electrosurgery, brain operations may come to be regarded with less apprehension in a few years.

Electrical Induction of Medicines

Recently some medical investigators have used direct current for the conduction of certain powerful pharmacologic agents through the skin. A few physicians are enthusiastic about the method, claiming that it is superior to the conventional subcutaneous injection of drugs and to other common methods of inducing medicines through the skin (such as massage). Some localization of medication has been claimed to be possible by this method, but it is not generally acknowledged.

Strictly scientific evaluations have not been ventured by medical authorities, because the experimental work thus far has not been sufficiently comprehensive, but the introduction of drugs into the body electrically has been criticized as lacking adequate control.

The Need for Co-operation Between Physicians and Electrical Engineers

Although the foregoing exposition is cursory and necessarily limited, it is intended to provide some indication of the enormous scope of electrical applications possible in medical science. To treat the subject adequately would require many volumes written by one familiar with electrical engineering, theoretical physics, and medicine. Even a casual survey of the literature available on the subject shows that but few physicians have any great familiarity with the physics of electrical apparatus, and perhaps fewer engineers have any conception of the physiological significance of the processes served by the machines they create. The sciences of both electricity and medicine are still immature, but the rapid advances they have made in combination suggest that more concerted effort might result in a new hope for the annihilation of human disease.

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Low-Voltage Fluorescent Lamps

By G. E. INMAN R. N. THAYER

Colored light usually is obtainable from incandescent lamps only by means of some special filtering material, at relatively low efficiency. Now a new type of lamp, which is tubular in shape and contains a powder that becomes fluorescent in the presence of ultraviolet radiation, produces white light similar in character to daylight, as well as monochromatic light, at efficiencies much larger than those ordinarily associated with incandescent lamps.

FLUORESCENT lamps, that are simple in form and operate through suitable ballast from 115- and 230-volt a-c circuits are among the more important recent advances in lamp design. The lamps are tubular in form, and the fluorescent material is energized by a hot-cathode positive-column electric discharge. Just as a transformer converts one voltage to another, so the fluorescent powder adhering to the inner walls of the envelope converts the invisible ultraviolet radiation in a low-pressure mercury discharge into visible radiation, or light. Progress in the development of these lamps has resulted from a gradual increase in knowledge pertaining to hot cathodes, to the production of short-wave ultraviolet radiation, and to the manufacture of efficient fluorescent powders. The resulting lamp produces colored light many times more efficiently than do present light sources. In addition, fluorescence provides a means of producing for the first time a practical source of white light matching daylight in appearance, efficiently and with low power inputs. Much concentrated effort has been spent in obtaining the desired electrical characteristics of the lamp and on the design of efficient ballast equipment. The lamps described here are in one of several classes of lamps now being developed.

General Characteristics of the Lamp

To obtain the positive-column type of discharge found most efficient for this lamp, the length of the tube should be several times its diameter. One electrode, which serves alternately as cathode and anode, is sealed into each end of the tube. The electrodes are small coils of tungsten wire coated with some material such as barium and strontium carbonates to improve their emissivity. During manufacture these carbonates are changed into oxides. The tungsten wire is small, so that it may be heated sufficiently by the energy of the discharge to provide good emission, and also to heat quickly when the lamp is started. Usually only one or two turns of the tungsten coils are heated to incandescence by the discharge, but the hot spots shift from one section to another during the life of the lamp.

The inner wall of the tube is coated with a thin layer of fluorescent material (also called the phosphor). Inside coating, besides its usual advantages, is essential because the ultraviolet radiation that energizes the phosphor will not pass through ordinary glass. The coating must have sufficient thickness to absorb the impinging ultraviolet radiation, yet must be so thin that it will not absorb too much of its own light or of the light internally directed from the opposite side of the tube. The evolution of a process for obtaining smooth, uniform coatings and lamps of uniform color and efficiency has required much painstaking effort.

The assembled lamp, consisting only of this coated tube and the sealed-in electrode at each end, is evacuated, and the carbonates on the electrodes are decomposed as in radio tube manufacture. A little argon (to facilitate starting) and a small drop of mercury are admitted to the tube and remain without cleanup for the life of the lamp. The resulting structure is simple yet sturdy, as shown in figure 1. Since there is no filament or supporting structure of any kind between the electrodes, the lamp is more rugged than filament lamps of the same size and shape, and withstands far more shock and vibration.

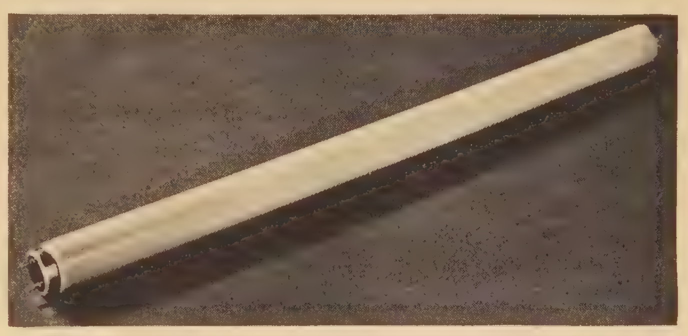

Figure 1. One of the new fluorescent lamps

Design of the Lamp

Choice of lamp dimensions and electrical values is determined not only by the maximum luminous efficiency, but also by numerous other factors, such as useful total light output, adaptability to starting and running on standard line voltages, suitable voltage drop and minimum

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Essential substance of a paper scheduled to be presented at the AIEE summer convention, Washington, D. C., June 20–24, 1938.

G. E. INMAN and R. N. THAYER are employed in the lamp development laboratory of the Nela Park works of the General Electric Company, Cleveland, Ohio. The authors acknowledge especially the assistance of Doctor B. T. Barnes, of the Nela Park laboratory, for the curves on spectral energy distribution; and of M. A. Edwards, Schenectady, N. Y., for the development of the resonant circuit.

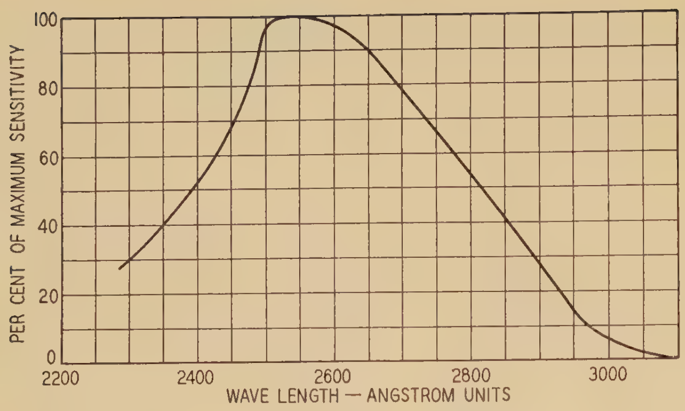


Figure 2. Curve showing relative sensitivity of the zinc beryllium silicate phosphor to ultraviolet radiation of various wave lengths. The peak at or near 2,537 angstrom units is characteristic of several phosphors

power loss in ballast equipment, esthetically pleasing proportions, low surface brightness, and commercial adaptability to manufacture, shipment, and use. Any choice requires compromises, and only a few variables can be considered here. Most activity has been concentrated upon tubes having a diameter of one inch and a current rating of about 0.25 ampere.

Mercury is used as the vapor for the discharge in fluorescent lamps because of its high efficiency in producing short ultraviolet radiation of a single wave length at its resonance line of 2,537 angstrom units. This efficiency is dependent upon the current density to a great extent. The lower currents are more efficient and at 0.25 ampere, which is the approximate value for the lamps described, the conversion efficiency is about 50 per cent. As shown by the example given in figure 2, the fluorescent materials selected produce light most efficiently for ultraviolet radiation of about this wave length, thus forming an ideal combination. No other measured spectral line of the low-pressure discharge in mercury vapor amounts to more than two per cent of the input power; consequently, the line at 2,537 angstrom units reasonably can be considered to be the chief exciter of fluorescence in these lamps. The presence of fluorescent material on the inside of the tube has no appreciable effect on the operation or characteristics of the discharge.

Temperature is a critical factor in the efficiency of producing radiations at 2,537 angstrom units in a low-pressure mercury discharge. Figure 3 shows that the efficiency is highest at 40 degrees centigrade. Consequently, a lamp operating at its most efficient temperature will be only from 15 to 20 degrees centigrade hotter than normal room temperature, and to that extent is a "cold light." Lamps must operate at temperatures higher than this optimum point in order to obtain larger power input and higher light output in tubes of the same dimensions. By using a power input lower than that giving the optimum temperature, efficiency losses from low temperature may be compensated by the advantage of lower current density. In table I the lamps having diameters of one inch operate at the optimum point; the lamps having diameters of one and one-half inches operate below it. The larger diameter was chosen to secure lower surface brightness and less glare. At lower temperatures, such as zero centigrade, very little ultraviolet radiation is produced because insufficient mercury is vaporized. To maintain normal light output at such an ambient temperature, the lamp must be jacketed or shielded to conserve heat.

Table I. Characteristics of Some Fluorescent Lamps

Length	Diameter	Watts	Volts	Amperes	Approximate Lumens Per Watt of a Green Lamp
18 inches	1 inch	15	63	0.27	60
18 inches	$1^1/_2$ inches	15	50	0.33	60
24 inches	$1^1/_2$ inches	20	65	0.35	65
36 inches	1 inch	30	115	0.30	70

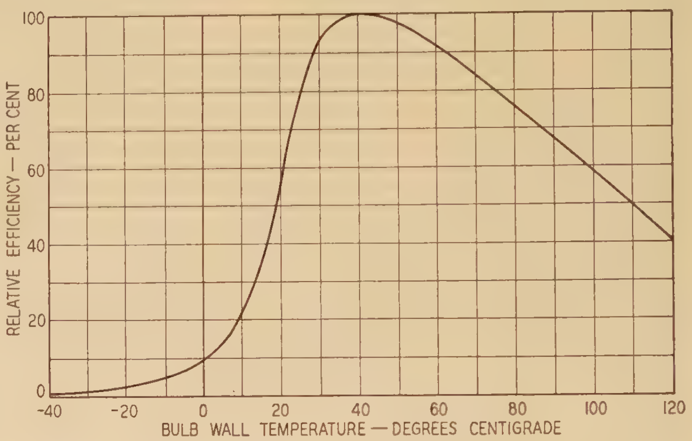


Figure 3. Relative efficiency of production of mercury resonance radiation (2,537 angstrom units) versus bulb wall temperature, for the positive column of a mercury discharge at 0.25 ampere in a tube of one-inch diameter. Fluorescent light output follows this curve closely

Lamp voltage also is an important factor in design. The voltage drop at the electrodes is practically constant, and is almost useless in the production of ultraviolet radiation and light. Consequently, the more the lamp voltage is increased by increasing the length of the tube or decreasing its diameter, the smaller in percentage this voltage loss becomes, as shown in figure 4. Another reason favoring high lamp voltage is that auxiliary loss becomes less as lamp voltage becomes a greater proportion of line voltage. For good stability of this type of discharge, the lamp voltage should not greatly exceed two-thirds of the available supply voltage, the remainder being consumed by suitable reactance.

Electrical Characteristics of Fluorescent Lamps and Circuits

The operating voltage of a fluorescent lamp may be divided into two components: the electrode drop and the potential gradient of the positive column. The former is fixed at some value between 12 and 18 volts, depending upon electrode size, cathode emission, and the gas used to fill the tube. The potential gradient is the voltage required per inch of tube to offset energy losses, such as the neutralization of ions at the walls, and the conversion of energy into radiation. The following empirical equations have been found to be valid for experimental lamps operating in the range of from 0.10 to 1.00 ampere:

For tubes one inch in diameter

$$E = \frac{2.73\,l}{0.56 + I} + 12.5 \qquad (1)$$

For tubes one and one-half inches in diameter

$$E = \frac{2.83\,l}{0.75 + I} + 12.5 \qquad (2)$$

where E is the lamp voltage, l the arc gap in inches, and I the current in amperes.

The starting voltage of a fluorescent lamp without preheating of the electrodes is about four times the operating voltage. For example, a lamp 18 inches long and of one inch diameter requires about 250 volts to initiate the discharge. Even at this voltage, a nearby plate or other metal surface connected to one end of the lamp or line, or to ground, usually is required.

Recent work has been concentrated on preheated-electrode starting because lamp life is greatly prolonged and end blackening is reduced by eliminating the sputtering of electrode material that occurs with cold starting. Also the required starting voltage is reduced, and may drop to 115 volts, if the electrodes are heated sufficiently. The circuit most easily explained is shown in figure 5*A*. Electrode and reactor design are so correlated that the electrodes are heated to incandescence after the switch is closed. Opening the switch by hand, or automatically by a thermal switch after one or two seconds of heating, produces a surge from the reactor, which easily starts the discharge. A modification of this circuit is a vibrator element built on the reactor, or employed separately. In this instance the circuit is repeatedly opened and closed, with the electrodes gaining heat at each contact until the discharge starts. The operating current then produces a field strong enough to hold the vibrator contacts open. The simple reactor consumes from one to three watts, depending upon its size. The semiresonant circuit shown in figure 5*B* provides simultaneously some voltage boost and electrode-heating current, low power loss, and automatic action with no moving parts. By suitable choice of inductance and capacitance values, and by correct proportioning of the saturation characteristics of the inductor, a combined value of voltage across the lamp and electrode-heating current assures lamp starting. As soon as the lamp starts, it shunts the parallel circuit and runs at an operating current determined by the series unit. Energy lost in the parallel circuit is less than a watt, and the entire circuit may consume only 17 or 18 watts for a 15-watt lamp.

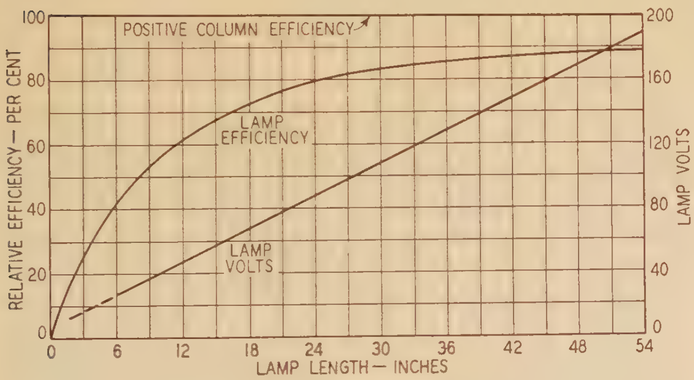


Figure 4. Lamp efficiency relative to positive column efficiency, and volts for various lamp lengths. The arc gap is about one and three-quarter inches less than over-all lamp length

Table II. Approximate Energy Utilization in a 15-Watt Fluorescent Lamp

	Efficiency of Process
Conversion to 2,537 angstrom units	50 per cent
Quantum conversion of 2,537 angstrom units to visible radiation (5,100 angstrom units)	50 per cent
Perfection of phosphor	60 per cent
Transmission of envelope (Covers bulb and base absorption)	90 per cent
Over all efficiency	13 per cent

The power factor of most fluorescent-lamp circuits is approximately equal to the ratio of lamp voltage to line voltage. For example, a 65-volt lamp in the circuit of figure 5*A*, assuming a line voltage of 115, operates at about 0.57 lagging power factor. If the circuit constants are predominantly capacitive instead of inductive, the power factor has the same value, but is leading.

Characteristics of the Light Output

The outstanding advantage of the fluorescent lamp is its ability to produce colored light at efficiencies far exceeding those of filament lamps. Experimental 15-watt green fluorescent lamps have operated at 70 lumens per watt. As compared with about 0.3 lumen per watt for certain 60-watt green filament lamps, this represents an efficiency gain of about two hundredfold. The corresponding efficiencies for blue lamps are 18 as compared with about 0.3,

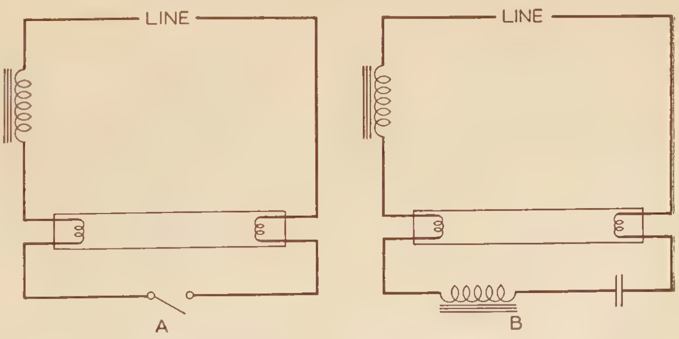


Figure 5. Operating circuits for fluorescent lamps

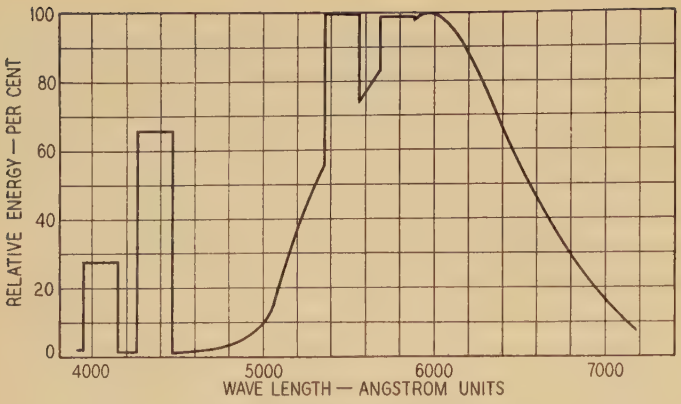


Figure 6. Spectral energy distribution of the radiation from a fluorescent lamp coated with zinc beryllium silicate phosphor. The curve for the phosphor alone is smooth. The block peaks are representations of the visible lines from the mercury discharge, plotted as though 200 angstrom units wide. The combined radiation matches the color, but not the spectral energy distribution, of a black body at about 2,800 degrees Kelvin

a gain of about fiftyfold. For other colors the gain is less spectacular, but still the efficiencies or fluorescent lamps are several times the corresponding efficiencies of filament lamps. Fifteen-watt fluorescent lamps of the same color as daylight have been made with efficiencies of about 30 lumens per watt; obtaining the same amount of light from a filament lamp, with a suitable filter to duplicate daylight, requires 150 watts, or ten times as much power and heat.

On basis for such great gains in special colors is that phosphors inherently produce a certain color, determined by their atomic and crystal structure. As shown in figure 6, spectral-energy distribution measurements typically show a peak region, which in this instance is at 5,950 angstrom units (yellow). In filament lamps, color must be produced from a source giving a continuous spectrum by the subtractive method of using a filter that absorbs all light except light of a desired color. A second basis for efficiency gains is that a large percentage of input energy is converted into usable radiant energy. A 40-watt filament lamp, for example, converts about seven per cent of its input energy into visible radiant energy, and most of the remainder is converted into infrared radiation, which is not convertible into light. Despite the efficiencies of utilization of a fluorescent lamp as shown in table II the net percentage of energy available for light production is about twice that of filament lamps.

Under external light the phosphors used in these lamps all appear white, regardless of their color during fluorescence. As a result of this whiteness, the familiar yellow, green, and blue lines of the mercury discharge pass through the fluorescent coating on the tube with little absorption, and contribute about 3.5 lumens per watt to lamp efficiency. Figure 6 shows these lines superimposed on the fluorescent spectrum. Because of their intensity, the production of fluorescent lamps with a narrow band of colored light, such as deep red, may require a colored enamel or filter. On the contrary, where it is desired to avoid any sharp peak of energy, as for daylight lamps, several phosphors may be mixed together to give a more nearly uniform spectral energy distribution.

Some phosphors, such as green and pink, inherently possess some lag, and continue to emit light after the exciting source is removed, so that 15-watt fluorescent lamps using such phosphors show no more flicker on 60-cycle supply than do regular 25-watt 115-volt filament lamps. Other phosphors, such as blue, have no measurable lag, and follow closely the starting and extinguishing of the discharge on each half of the cycle. The condensation of mercury at low temperatures not only lowers the production of ultraviolet and of visible light, but raises the starting voltage so much that special ballast equipment may be required; hence, fluorèscent lamps are best used indoors, or outdoors in mild weather.

About every new type of lamps the engineer asks, "What is its effective life?" In the use of fluorescent lamps, as in vapor lamps generally, useful life may be limited either by the number of times the lamp is started or by the loss of light with continued operation. Frequent starting of lamps causes eventual failure to start, because the emissive material sputters off. If lamps are operated continuously, or for several hours following each start, they may last several thousand hours, but at steadily decreasing light outputs until replacement is justifiable economically. The amount of decrease varies with different phosphors. Fluorescent lamps under average operating conditions are expected to last longer than filament lamps and to have lumen maintenance comparable with that of filament lamps of the vacuum type.

One suggested use of the new tubular fluorescent lamps is for flooding ceilings with colored light. As shown here the lamps are concealed within a trough suspended from the ceiling

Television Transmission by Coaxial Cable

By M. E. STRIEBY
MEMBER AIEE

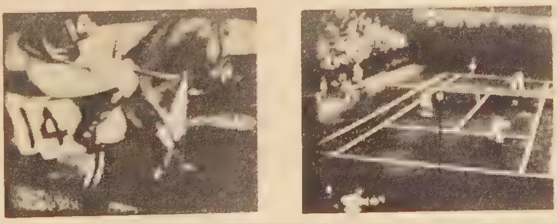
Coaxial cables were developed originally to provide large groups of telephone channels, but their wide frequency range has led to experiments with the transmission of signals for television. High-quality signal generating and receiving equipment was used to send 240-line motion-picture images from New York to Philadelphia, as described in this article; distortion introduced by the wire-line circuits could be made so small as to be inappreciable.

REPORTS that have been made on the progress in television development increase the expectation that the commercial broadcasting of visual programs soon will be realized. In anticipation of this, the Bell Laboratories has been engaged for some time in the development of wire-line circuits for transmitting television signals between studios and broadcasting transmitters, or between cities, as may some day be required if television follows in the footsteps of sound-program broadcasting.

The wide frequency bands required for television and the dearth of available frequencies appear to force the broadcasting of television signals into the ultrahigh-frequency range. At these high frequencies, the coverage which can be obtained from a broadcasting station is very limited as compared to that obtainable in the sound-broadcasting frequency range. Hence, if television programs are to reach large sections of the country simultaneously, the provision of interconnections between large numbers of television broadcasting transmitters will become even more important than it is today for sound broadcasting.

Coaxial cables have received much publicity as transmission lines for television. Actually that use is a byproduct that had little or nothing to do with the original conception. The idea of a coaxial cable or other medium for the transmission of very broad frequency bands originated as a telephone development in the United States.[1] The first lengths of such cable for broad-band transmission were made here and its first use for the transmission of a large number of simultaneous telephone conversations was between New York and Philadelphia.[2] In the United States the important reason for developing coaxial cable systems was, and still is, that they appear to offer material economies in the provision of large groups of long-distance telephone facilities. Television has been incidental.

Recently experiments have been made on the transmission of television signals over the coaxial cable between New York and Philadelphia. This cable contains two coaxial conductor units within a lead sheath about seven-eighths inch in diameter as indicated in figure 1. Two coaxial units were provided because, for long-distance telephone operation, four-wire operation is preferable, one coaxial unit being employed for transmission east to west and the other west to east. Each coaxial unit is made up of a 13-gauge inner conductor on which hard-rubber disks have been placed at intervals of three-fourths of an inch. The outer metallic tube is made up of nine overlapping copper tapes so designed that they form essentially a solid copper tube about 20 mils in thickness and 0.267 inch in inside diameter.



Photographs of the receiving tube during transmission; in the tennis match the ball itself shows and its movement could be followed

The transmission loss of this circuit as a function of frequency is shown on figure 2 together with the portion of the attenuation that is contributed by conductance losses. Inasmuch as the intention is to use these conductors at very high frequencies, a high-grade insulating material was used with the result that the conductance losses are small. It should be noted that the attenuation increases very nearly as the square root of the frequency.

In order to transmit high frequencies over long distances, a great deal of amplification is obviously required. The New York–Philadelphia cable was initially equipped to handle a band of 1,000,000 cycles. Its over-all attenuation at one megacycle is approximately 600 decibels. In order to reduce this to a usable amount, ten repeater points were provided at intervals of about ten miles, each having an amplification at the top frequency of about 60 decibels. These repeaters were so designed that they provided less gain at low frequencies than at high frequencies in approximately the same degree as the line had less attenuation. To make up for certain cumulative irregularities an equalizer was built and added to the over-all circuit. The net result was a transmission path which had approximately zero loss over the whole band which it was desired to use from 60 to 1,000 kilocycles as shown in figure 3.

Another complicating factor, however, is involved, as

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Crosstalk and Noise Features of Cable Carrier-Telephone System

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CROSSTALK and noise are important factors in cable carrier transmission as outlined in the paper "A Carrier Telephone System for Toll Cables" by Messrs. C. W. Green and E. I. Green. Crosstalk and noise limit the number of carrier channels which can be utilized in any one cable, not only by limiting the number of channels which can be placed on a single pair, but by limiting the number of pairs which can be used. Noise also controls the transmission loss which can be permitted between repeaters. Without the crosstalk and noise reduction measures described in this paper, the number of carrier channels per cable would be so few and the spacing between repeaters so short, that the type-*K* carrier system would be impracticable.

Crosstalk

To utilize existing toll cables in the Bell System for frequencies up to 60 kilocycles required the solution of many new crosstalk problems because: (1) crosstalk increases rapidly with the frequency; (2) nonloaded carrier pairs due to their high speed of propagation are especially suitable for very long distances and hence the crosstalk requirements per unit length are relatively severe; (3) the large gains of the carrier repeaters amplify certain crosstalk currents much more than in the case of voice frequency circuits.

Two general effects need to be considered: intelligible crosstalk must be prevented; and a large number of circuits crosstalking into a particular circuit must not contribute an undue amount of noise. The second effect is called babble, since it consists of a multiplicity of unrelated voice sounds which, in the aggregate, are unintelligible.

An important feature is the use of different cables for opposite directions of transmission. This makes the major crosstalk problem the reduction of crosstalk between pairs in the same cable used for transmission in the same direction. The crosstalk currents due to transmission at one end of a disturbing circuit through the distributed couplings with a disturbed circuit tend to arrive at the distant end at the same time since the currents via any of the couplings travel substantially the same distance. This makes it possible to greatly reduce the total effect of these distributed couplings by the use of small adjustable mutual inductance coils connected between pairs at one point in each repeater section.

If nothing more were done, there would still be objectionable crosstalk since currents from the outputs of carrier repeaters could crosstalk into voice-frequency circuits and these circuits could then again crosstalk into other carrier-frequency circuits at points near their repeater inputs. This effect is minimized by transposing the carrier pairs from one cable to the other at carrier repeater points.

At common voice-frequency and carrier-frequency repeater points there would be an unsatisfactory crosstalk path from a carrier repeater output into all the wires not used for carrier frequencies and from them through coupling between office wiring into similar wires in the other cable and finally into carrier repeater inputs in the second cable. This crosstalk is minimized by the use of carrier-frequency suppression coils in the voice-frequency circuits. These coils also serve the purpose of preventing carrier frequency noise originating in voice frequency circuits from being transmitted into the cables and inducing noise at points near carrier repeater inputs.

NEAR-END CROSSTALK

Near-end crosstalk is the result of coupling between circuits transmitting in opposite directions, while far-end crosstalk is the result of coupling between circuits transmitting in the same direction. Near-end crosstalk coupling between different carrier circuits of the same frequency must be kept very small, particularly near a repeater point, since crosstalk from the output of a repeater into an opposite directional pair near the input of its repeater will be greatly amplified by this repeater.

Crosstalk between carrier circuits within the offices is kept low by careful shielding, segregation, suppression of spurious paths through battery supply, common grounding arrangements, etc.

Since the type-*K* system operates on a "four wire" basis, different electrical paths are used for opposite directions of transmission. Satisfactory near-end coupling in the outside plant is obtained, therefore by placing east bound pairs in one cable and west bound pairs in another. When two cables have relatively heavy sheaths as in the larger Bell System cables, their coupling is sufficiently small even with the two cables in close proximity.

INTERACTION CROSSTALK

The crosstalk currents from a carrier repeater output into voice-frequency circuits in the same cable must be limited, since they crosstalk again into carrier circuits near repeater inputs and, consequently, are amplified by the high-gain repeaters. Intermediate circuits most responsible for crosstalk of this type are made up of combinations of pairs and phantoms and the sheath, i.e., longitudinal paths.

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1. For all numbered references, see list at end of paper.

One case of crosstalk of this kind would occur if the same cable were used for carrier pairs transmitting in the same direction on both sides of a repeater. This is prevented by transposing carrier pairs from one cable to the other at each repeater point, as shown on figure 1.

A second interaction crosstalk problem is encountered at the common voice and carrier repeater points and involves coupling between cables as well as in the same cable. Here the coupling path is from carrier repeater outputs to intermediate circuits in the same outside cable, back into the common office over these intermediate circuits and then via office coupling to intermediate circuits in a second outside cable and from there to carrier repeater inputs connected to pairs in the second cable. Referring to figure 1, a set of noise (and crosstalk) suppression coils is encountered in this path. The high longitudinal circuit impedance of these coils minimizes this interaction crosstalk.

Far-End Crosstalk

Far-end crosstalk currents are subjected to line attenuation and amplification similarly to the main transmission currents, and do not have extra amplification as in the case of near-end crosstalk. Furthermore, far-end crosstalk currents due to couplings at different points along the line tend to arrive at the distant end of the disturbed circuit at the same time. Hence a considerable portion of the far-end crosstalk over the type-*K* frequency range, which occurs between circuits transmitting in the same direction in the same cable, can be neutralized by introducing compensating unbalances at only a comparatively few points, such as one per repeater section. The far-end crosstalk reduction problem is greatly simplified because phantom circuits are not used for carrier operation.

Theoretically, for the same precision of match between the impedances in the two directions at the balancing point, the crosstalk reduction would be about the same whether the balancing is done at an intermediate point or at either end of a repeater section. Balancing will be done at repeater inputs rather than at an intermediate point, such as the middle, because it is practicable to obtain repeater impedances matching the average line impedance sufficiently well so that the effectiveness of balancing is reduced only slightly.

Nature of Far-End Crosstalk Coupling

The coupling between two cable pairs in a short length may be represented by a mutual admittance and a mutual impedance. The former is due almost entirely to capacitance unbalance, which varies but little with frequency, so that its effect could be practically balanced out by means of a simple condenser. The latter, however, involves a complex mutual inductance of the form $M_a + j\,M_b$, because of the proximity effect of the wires of a pair and of other cable conductors.[1] As shown on figure 2, both components vary considerably with frequency; M_a on the average decreasing as the frequency increases while M_b in the general case is of negative sign and reaches a maximum value at 56 kilocycles.

Type of Balancing

To obtain maximum reduction in crosstalk it would be necessary to use a condenser for balancing the mutual admittance and an inductance coil for balancing the

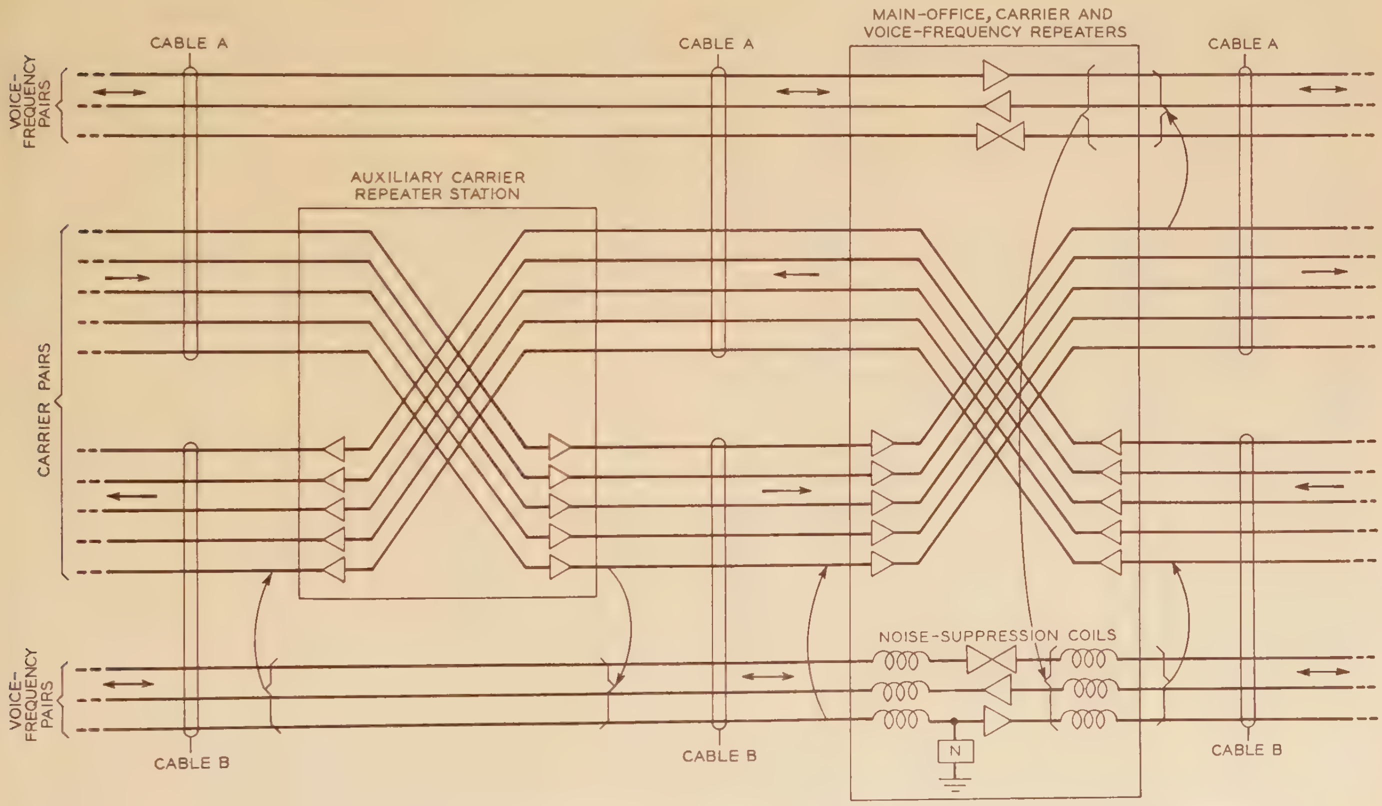


Figure 1. Schematic showing carrier pairs transposed between cables, coupling paths and noise suppression coils

quencies from 800 kilocycles down to and including direct current. The d-c or zero-frequency component controls the general level of brightness of the picture. Where the general level of brightness changes slowly, it results in a component of very low frequency. A composite picture can be imagined which will produce a pronounced component at any given frequency, hence, it is deemed important to transmit the entire band from 0 to 806 kilocycles.

Receiving Device

At the receiving end an effort was made to obtain as high a degree of fidelity of reproduction as possible. No small factor in the success of the recent experiment was the special cathode-ray tube, designed by C. J. Davisson, used at the receiving end to display the transmitted picture. Some of the features of this tube are indicated schematically in figure 9. A stream of electrons from the cathode passes through a series of electron lenses which focus a narrow beam on an aperture 0.006 inch square. Between the lenses and the aperture, however, are two modulating plates connected to the incoming circuit in such a way that there appear on these plates potentials varying according to the voltage of the incoming signals. The effect of potential on these plates is to deflect the electron beam, and the conditions are such that at maximum strength of signal practically the entire stream of electrons passes through the hole and forms a brilliant spot of light on the front of the tube. As the signal decreases in strength, the electron stream is more and more deflected; less electrons pass through the aperture, and the illumination on the sensitized end of the tube decreases.

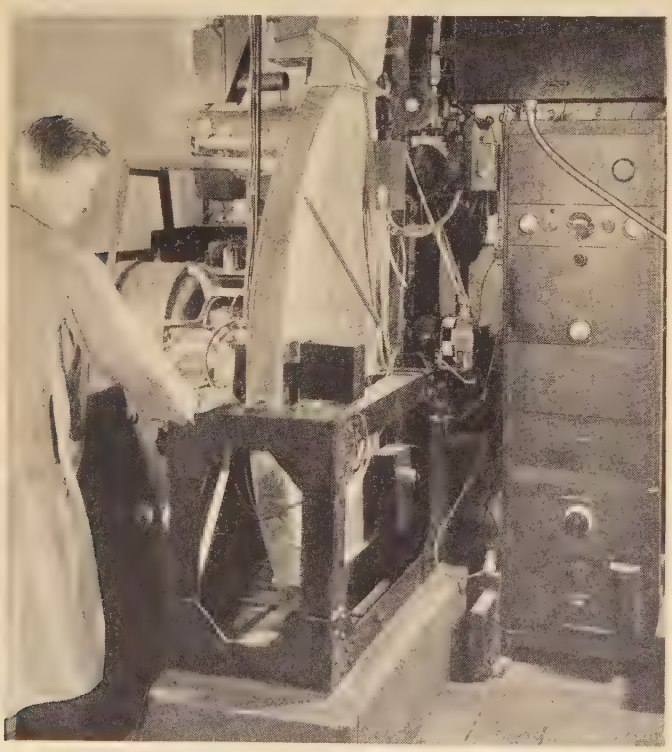


Figure 7. Mechanical scanning disk and associated experimental apparatus

In addition to these modulating plates, and placed between the aperture and the front of the tube, are two other pairs of plates mounted in planes at right angles to each other. The potential on one of these sets of plates, controlled by a frequency of 5,760 cycles, which is the frequency at which successive lines are scanned, varies in such a way that the beam of electrons passing through the aperture is swept across the front of the tube from left to right, exactly in synchronism with the scanning beam at the sending end. After the beam reaches the farther side of the picture, the potential on the plates is suddenly changed, and the beam is rapidly moved back to begin the next line. Due to a black mask down the far side of the film being scanned, there is no signal during this very short period while the voltage on the plates is changed, and thus the electron beam is deflected from the aperture and is not visible on the front of the tube during its return.

The potential on the other pair of plates is controlled at a frequency of 24 cycles per second, which is the rate of scanning successive frames. The effect of the potential on these plates is to deflect the electron beam downward in synchronism with the motion of the film at the sending end. This results in the passage of the electron beam across the front of the tube in successive rows, one below another. After the last row has been scanned, the voltage on the plates is changed and returns to the value that causes the beam to appear at the top line of the tube. A properly synchronized blanking-out pulse is introduced between successive frames of the film, so that no signal is received during this interval, and thus the passage of the electron beam from the bottom to the top of the frame is not visible.

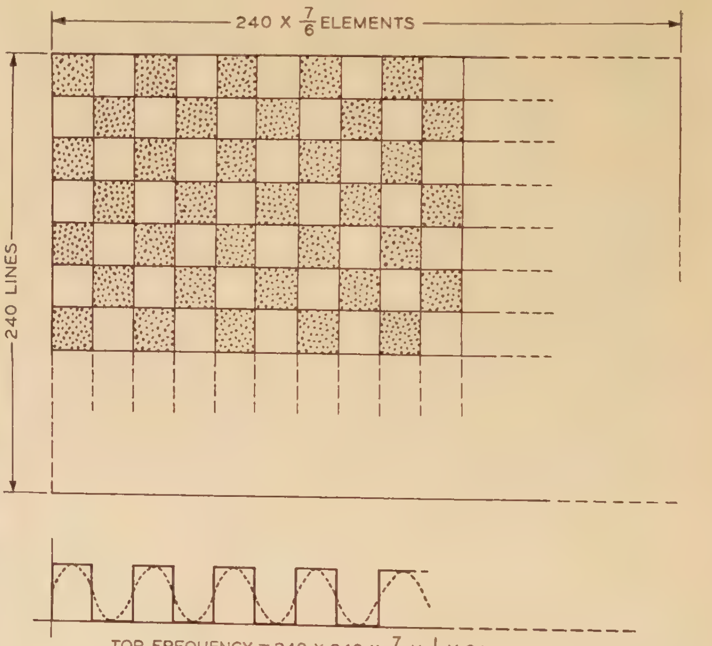

240 X $\frac{7}{6}$ ELEMENTS
240 LINES
TOP FREQUENCY = 240 X 240 X $\frac{7}{6}$ X $\frac{1}{2}$ X 24 = 806.4 KILOCYCLES

Figure 8. Diagram illustrating the resolution of an image into picture elements and the derivation of maximum frequency required for transmission

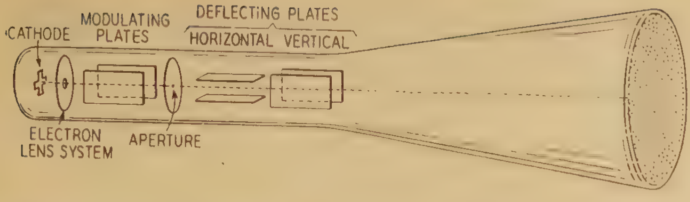


Figure 9 (above). Schematic diagram of the special cathode-ray tube used for viewing transmitted images

Figure 11 (right). Schematic diagram illustrating the processes of modulation and demodulation used in transmitting television signals over the coaxial line

Figure 10. One of the special cathode-ray receiving tubes

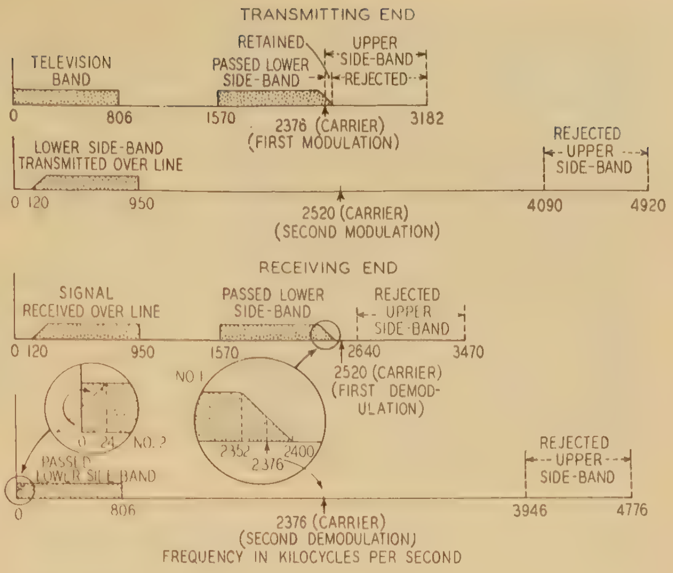


Figure 10 shows a photograph of one of these cathode-ray tubes. Because of the tube's superior design, the image is very sharp over the entire field and a wide range of brightness is secured. The chief factors in its success are the sharp focusing by the electron lenses, the linear deflection of the beam at the aperture, and the great length of the tube, which makes it necessary to deflect the electron beam over only a narrow angle to cover the seven-by-eight-inch field. Since this trial was a test to determine the capabilities of the system, such matters as size and cost, which would be important with commercial receivers, were not controlling.

Modulation System

The frequency band which was generated at the sending end as noted before was 0 to 806 kilocycles. The coaxial-cable system used could not transmit this band, because repeaters were not designed to pass frequencies below about 60 kilocycles. This limitation was incorporated in the original design because the cable offers insufficient shielding to various disturbances at low frequencies. For television transmission it was necessary, therefore, to raise the television-signal band to a higher-frequency position before attempting transmission over the line. Several considerations led to the decision to raise the entire frequency band 144 kilocycles for transmission over the coaxial cable.

Where such a wide frequency band is to be raised by an amount less than the width of the band itself, a single modulation is not generally satisfactory. The products of modulation include the original frequency band as well as the upper and lower sidebands, so that in the lower sideband there will be a confusing jumble of frequencies in the modulator output. For this reason a double modulation method was used for the recent experiments.

The modulating scheme employed can be followed with the help of figure 11, which shows the two modulating steps at the sending end and the two demodulating steps at the receiving end in four lines beginning at the top. A carrier of 2,376 kilocycles is used for the first modulation, which results in a lower sideband from 1,570 to 2,376 kilocycles and an upper sideband from 2,376 to 3,182 kilocycles. The carrier itself is eliminated in the balanced modulator. The output of this modulation is passed through a filter, but because the two sidebands touch each other at 2,376 kilocycles, the filter cannot cut off all the upper sideband. At the output of this filter there is thus the lower sideband plus a small amount of the lower part of the upper sideband. The upper sidebands from all subsequent modulations are readily eliminated by filters because of the wide separation.

The carrier for the second modulation is 2,520 kilocycles, and the lower sideband extends from 950 down to 144 kilocycles plus the vestigial upper sideband remaining from the first modulation which extends down to 120 kilocycles. The high-pass filter following this modulation is accurately designed to pass with controlled attenuation a group of frequencies just above 144 kilocycles and the vestigial sideband. The resulting single sideband, extending from 120 to 950 kilocycles, is then passed over the coaxial cable.

At Philadelphia the received signal, together with a carrier of 2,520 kilocycles, is applied to the first demodulator, and the lower sideband, from 2,400 down to 1,570 kilocycles, is passed to the second demodulator where a carrier of 2,376 kilocycles is applied. The lowest frequency of the lower sideband, 1,570 kilocycles, is con-

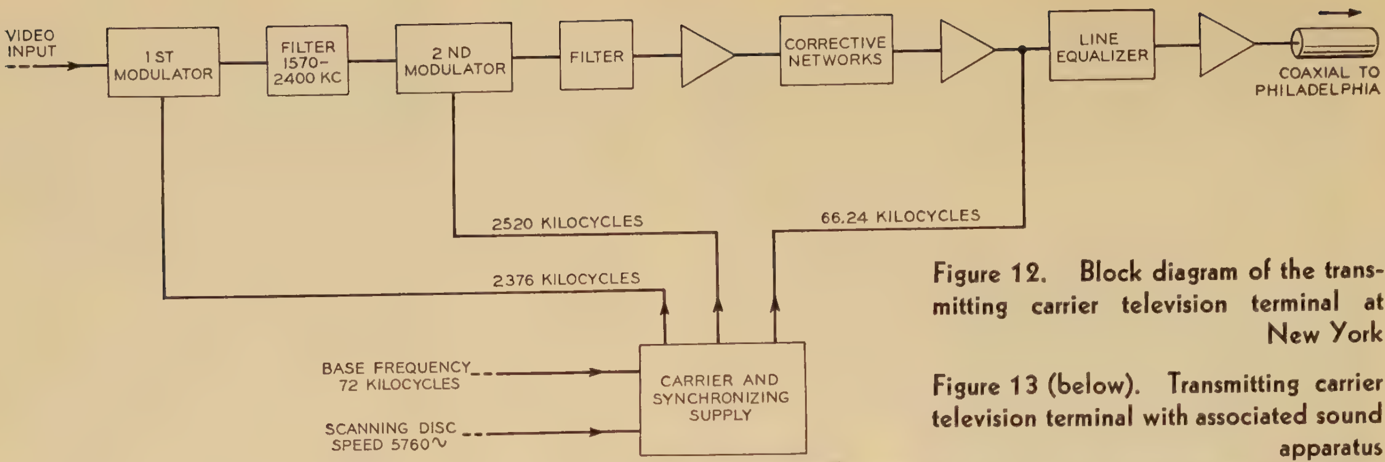
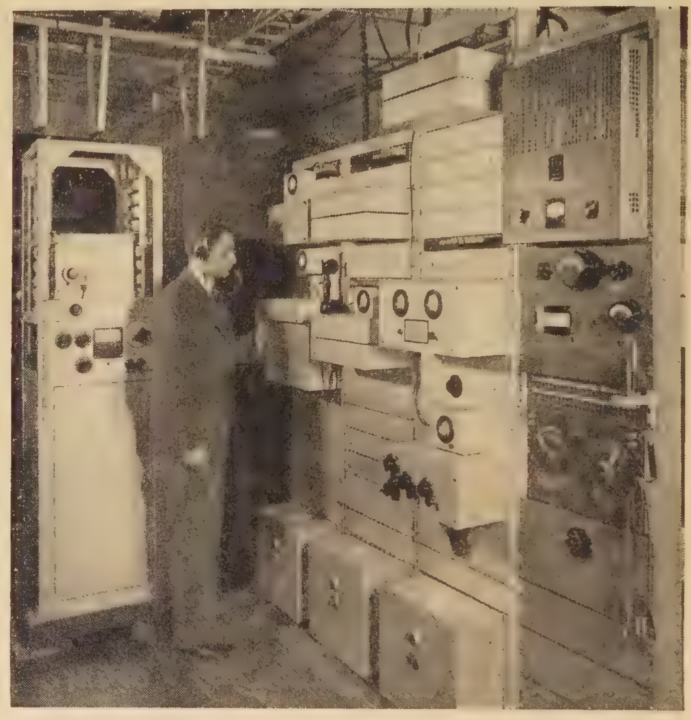


Figure 12. Block diagram of the transmitting carrier television terminal at New York

Figure 13 (below). Transmitting carrier television terminal with associated sound apparatus



verted to 806 kilocycles, becoming the highest frequency of the final demodulated band. The frequencies from 2,352 to 2,400 kilocycles have been somewhat attenuated by the high-pass filter mentioned above. The second demodulating carrier, 2,376 kilocycles, falls in the middle of this attenuated band as shown in inset number 1 in figure 11. Frequencies extending about 24 kilocycles above the carrier are inverted by the demodulation, and superimposed upon the corresponding frequencies just below the carrier. The magnitude and phase of these components are proportioned by the high-pass filter and an equalizer so that the over-all result, when they are superimposed, is an essentially flat transmission band from zero to 806 kilocycles.

These steps of modulation involve many difficulties. In the first place, the signal level must be carefully controlled so that on the one hand it does not sink into the background noise, while on the other hand it must not be raised to such high levels that unwanted modulation products are produced in too great magnitude. The first modulator presents some special problems. It must accommodate all frequencies from 0 to 806 kilocycles. In order to eliminate the carrier, it must be balanced out to a very high degree—about 80 decibels below the signal level in this case. The reason the carrier must be wiped out so completely is that the zero-frequency component of the signal is identical with the carrier at the output and hence the true d-c value of the signal must be exceptionally free from carrier interference.

Referring to figure 12, the next piece of apparatus is a band filter to eliminate the video signal and cut off the top edge of the band. Then follows the second modulator which is quite conventional. A low-pass filter is next and is very important as it performs part of the function of cutting off and adjusting the vestigial sideband. Then follows an amplifier, a predistorting network to equalize partially the amplitudes of the different components of the signal, an aperture equalizer to correct for the fact that the scanning spot is of finite size, a terminal equalizer to make up for irregularities in the over-all setup, and other amplifiers.

The carrier apparatus at the sending end is shown by figure 13. It is mounted in rather conventional form except for the first modulator which was arranged to minimize the effect of low-frequency vibrations. At the receiving end about the same apparatus is required in the inverse order and it will not be discussed in detail.

Carrier Supply

Another feature of this system was the provision of accurately spaced carriers for the various modulating operations. The Bell System four-kilocycle standard was used to produce a 72-kilocycle (18th harmonic) base-frequency signal which could be transmitted over the line and so tie the transmitting and receiving ends together. From this, by harmonic generation, the carriers used in the two steps of modulation were produced, being the 33d and 35th harmonics.

To synchronize the scanning at the receiving end with the transmitting disk required another direct tie. The disk is driven by a d-c motor and its speed cannot be kept very constant. By means of an auxiliary lamp and photoelectric cell, the frequency with which one scanning line followed another—approximately 5,760 per second—was obtained. This was modulated with the 72 kilocycles mentioned in the preceding paragraph and transmitted over the line as a lower sideband at 66.24 kilocycles. At the receiving end by demodulation, the exact line speed, approximately 5,760, is obtained and used to drive the horizontal sweep. The vertical sweep is obtained by generating the 240th subharmonic of this—namely, 24 cycles per second.

Line Equalization and Test Results

With reference now to the line transmission problem, the signals which might be transmitted in the general case are indicated in figure 14. They include the pilot channels used for automatic transmission regulation at 60 and 1,024 kilocycles. For convenience, one telephone channel with a carrier at 64 kilocycles is indicated as an order wire, and a wide-band program channel with carrier at 84 kilocycles to transmit the sound. These, of course, could be provided with ordinary telephone facilities. The base frequency of 72 kilocycles and the disk synchronizing sideband at 66.24 kilocycles are also included. For the television signal itself the band from 120 to 950 kilocycles is provided. Actually in the tests to Philadelphia, automatic regulation was not needed and a separate wire line was used for synchronization.

It was necessary to provide networks and equalizers to insure that the coaxial line did not distort the ultimate image by unequal attenuation, resulting in amplitude distortion, or by unequal time of transmission, causing phase distortion. The actual attenuation characteristics of the line[5] and the over-all result were shown in figure 3. The requirements for phase distortion are rather difficult to meet. The details in the scanned picture result in various frequencies of the electrical signal, and if these details are to appear in the reproduced picture in the same relative position as in the scanned picture, it is essential that all frequencies be received in very closely the same relative time relationship as they are generated. With reference to figure 8, the assumption was made that no picture element could be displaced by more than about half its width. This led to the decision to hold frequencies between 806,000 and 3,000 cycles to a delay distortion of about 0.3 microsecond. For a similar degradation of detail in the vertical direction, the permissible delay distortion is 280 times as great. In a system of this type, this is very easily obtained. The actual circuit roughly met these requirements as indicated by figure 15, which shows the phase-delay characteristics of the line, repeaters and loss equalizers, and of the over-all circuit at the frequencies used for transmission.

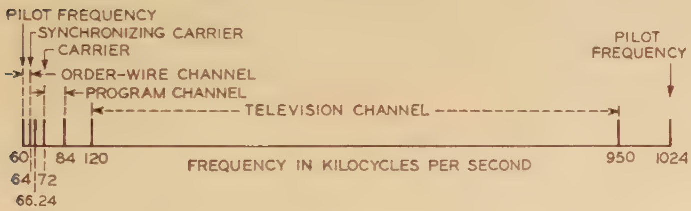


Figure 14 (above). Frequency allocation for a television transmission system with associated control circuits

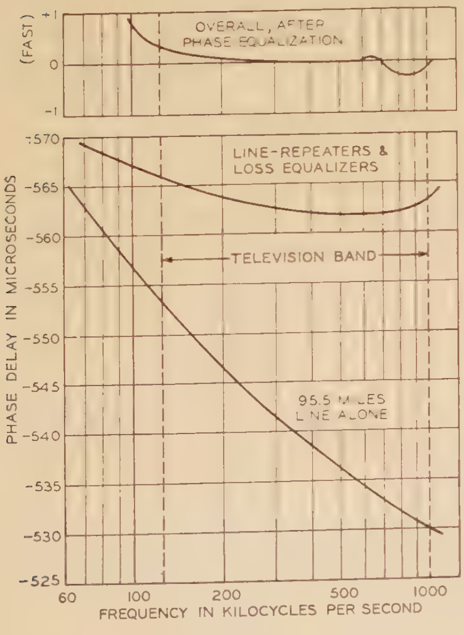


Figure 15. Phase delay of New York – Philadelphia television circuit

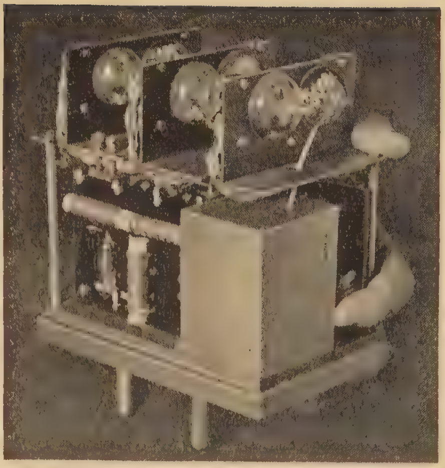


Figure 16. Two-megacycle amplifier under development for experiments on the coaxial cable

Noise or interference is very annoying in television transmission, and pattern, or single-frequency interference, is particularly objectionable. The permissible noise or interference depends on the amplitude range of the reproduced picture. During these experiments, it was found that a substantially linear response could be obtained over a signal-current range of about 20 decibels—(a brightness ratio of ten to one). The actual reproduced pictures considerably exceeded this range—in fact a brightness ratio of 50 or 100 to 1 was realized. In these tests it was found desirable to hold random interference down about 40 decibels below the maximum signal, and pattern interference down at least 15 decibels more.

The engineers who worked on the system, and outside experts who observed it, expressed the opinion that the reproduced pictures in Philadelphia were substantially the same as those seen on a similar receiving device in New York, thus showing that the cable system itself introduced no appreciable distortion.

Further Development Now in Progress

As a result of the experimental transmission of the pictures over the coaxial cable from New York to Philadelphia it has been proved that wide-band signals of the type required for television can be satisfactorily transmitted over a coaxial-cable system, and that in such transmission the distortion introduced by the wire-line circuits can be made so small as to be inappreciable, in its effect on the received picture.

The work on these very-wide-band systems has only begun and repeaters and terminal apparatus are now under development capable of handling wider bands of frequency. At the present time work is under way on a two-megacycle system for telephone transmission and a trial installation is being made between New York and Princeton. The system will transmit a frequency band of about two megacycles corresponding to a capacity of 480 telephone circuits. Repeaters on this system will be about five miles apart and will consist of unattended boxes somewhat smaller than the one-megacycle repeaters illustrated hereinbefore, and placed either in manholes or on poles along the route. Within these boxes there are placed two amplifiers, one for eastbound transmission, the other for westbound, together with the necessary filters and power-supply apparatus. The actual amplifiers themselves are quite small compact units, one of which is shown in figure 16. Two megacycles, of course, is not a sufficiently wide band to transmit the present Radio Manufacturers Association standard 441-line television signal, but is a logical step toward more economical telephone circuits. Development is also under way on amplifiers capable of transmitting three-megacycle bands of frequency, which should amply satisfy the requirements for transmitting the 441-line television signals now envisioned as standard by the television industry.

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Today's Opportunity for the Young Engineer

By cultivating a practical point of view toward today's difficult situation the young engineer may gain experience at the very outset that will assist him in solving problems likely to recur again and again throughout his entire professional career

By W. H. HARRISON
PRESIDENT AIEE

YOUNG MEN these days ponder over the future, speculate on what it holds, not infrequently become so perplexed at the outlook that they wonder whether there is much in store for them—whether the industrial expansion has not run its course. This all too general train of thought prompted me to retrace the written record back to the period when the telephone received its first recognition, which was the birth of this great industry. This was at the Centennial Exposition held in Philadelphia, Pa., in 1876 to celebrate a century of our national life. This exposition evidenced in tangible form the tremendous advances of our material prosperity as contrasted with that of the old world. The marvels of mechanical ingenuity and of science and invention, and the engineering displayed there, must have stirred creative imagination as never before; and must have had a strong influence upon the years following.

In the brief period of approximately ten years following this exposition, numerous significant developments were initiated, including:

The commercial application of the telephone.
The electric arc lamp.
The electric incandescent lamp.
The multiple system of electric distribution.
Hydroelectric stations.
The a-c transformer and modern electric-power transmission.
The electric street railway.
Color printing.
The steam-electric generating station.

As an outgrowth of these advances, this same period witnessed the organization of many societies, such as the American Society of Mechanical Engineers and the AIEE. This ten-year period of 60 years ago created a milestone of human progress. The resulting integration of the constructive efforts of centuries almost immediately manifested itself in the formation of entirely new industries of unprecedented size which were destined to alter the

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Notes used by President Harrison at a conference of the Student Branches of the AIEE Great Lakes District held April 22–23, 1938, at the University of Illinois, Urbana.

In transmitting these notes for publication Mr. Harrison states: "In the preparation of these notes I discussed the subject with my associate O. W. Eshbach to whom I am indebted for some helpful suggestions."

entire scheme of human relationships. Their operation and influence on our lives and customs have revolutionized social intercourse, industrial relations, and management in such a way that the end is not yet in sight.

All the conveniences of transportation, communication, light, power, and a host of other things, are monuments of the material achievements that have resulted. In the early stages of this industrial revolutionary period, as there was before, as there has been ever since, and as there probably ever will be, there was much concern as to where all these scientific advances were leading the nation. We were reminded then, as we are now, that the application of science and engineering must be slowed up lest we suffer dire consequences from the nation's inability to assimilate these advances. In 1886 Carroll D. Wright, United States Commissioner of Labor, in the introduction to his annual report of that year made the following significant statement:

> "The rapid development and adaptation of machinery in all the activities belonging to production and transportation have brought what is commonly called overproduction, so that machinery and overproduction are two causes so closely allied that it is quite difficult to discuss the one without taking the other into consideration. . . . On all sides one sees the accomplished results of the labor of half a century. From a financial point of view, these accomplished results should always be good, but in many cases it is apparent that undertakings have proved deceptive and governments become needy and some . . . insolvent. Whatever may have been the financial results, industry has been enormously developed, cities have been transformed, distances covered, and a new set of economic tools has been given in profusion to rich countries, and in a more reasonable amount to poorer ones. What is strictly necessary has been done oftentimes to superfluity. This full supply of economic tools to meet the wants of nearly all branches of commerce and industry is the most important factor in the present industrial depression. It is true that the discovery of new processes of manufacture will undoubtedly continue, and this will act as an ameliorating influence, but it will not leave room for a marked extension, such as has been witnessed during the last 50 years, or afford a remunerative employment of the vast amount of capital which has been created during that period. The market price of products will continue low, no matter what the cost of production may be. The day of large profits is probably past. There may be room for further intensive, but not extensive, development of industry in the present era of civilization."

This quotation and many others that are available are characterized by a common factor: Little or no hope is offered for the future.

While most people during times when the outlook is most uncertain seem to hold the views illustrated by the foregoing quotation, some have the foresight and imagination to perceive that there is a still greater period ahead, that the general trend of our social welfare is upward from generation to generation, from century to century, with periods of depression which interrupt temporarily the upward progress. In 1830, at the time of a serious depression in Great Britain, Macaulay, the famous British historian, published an essay in the Edinburgh *Review*. Only a small part of it is quoted:

> "If we were to prophesy that in the year 1930, a population of 5 millions, better fed, clad, and lodged than the English of our time, will cover these islands . . .—that machines, constructed on principles, yet undiscovered, will be in every house—that there will be no highways but railroads, no travelling but by steam—that our debt, vast as it seems to us, will appear to our great-grandchildren a trifling encumbrance, which might easily be paid off in a year or two—many people would think us insane. . . .
>
> "Hence, it is, that though, in every age, everybody knows that up to his own time progressive improvement has been taking place, nobody seems to reckon on any improvement during the next generation.
>
> "We cannot absolutely prove that those are in error who tell us that society has reached the turning point—that we have seen our best days. But so said all who came before us, and with just as much apparent reason. . . ."

Here we are in the 1930's. We find ourselves with the rest of the world in a perplexed state of confusion. Young men on the threshold of their business careers are wondering what the future holds for them. They are wondering how well they shall be able to readjust their lives to the tune of tomorrow. They will do well to recognize that life is one continual period of readjustment. The readjustment of tomorrow is the first of a series. It now seems terribly difficult. It will not be difficult at all.

If a biologist, a historian, a politician, and an engineer were asked what the future holds, a different answer probably would be received from each. While all the answers would be interesting, the historian's would be most helpful in our day-to-day lives. In history we find recorded the experience of the human race since the earliest days of civilization. It is difficult to conceive how we can judge the probabilities of the future, except by the experience of the past. In spite of the dire prophecies that have been made, history records on the whole a gratifying, a really fantastic result.

Engineers are trained to be realistic, and not given to flights of fancy. To realistic men, on the surface it would seem, particularly in the electrical field, that hardly any frontiers are left to explore and to conquer. There is some reason for the query as to whether the industry which captured the imagination of our fathers by its feats of wonder and by its promises of immense growth and importance in the world, any longer offers romance. Electricity is so commonplace, it so regulates our day-by-day existence, that one might wonder what is left.

I am not a crystal gazer and have no power of prophecy. As a matter of fact the *present* always has engrossed me, for I believe that settling the problem of *today* frequently settles the problem of tomorrow. But as I have seen something of the road perhaps I can point out a few things that may help and encourage young electrical engineers about to embark upon their professional careers.

I am not going to suggest there are plenty of opportunities because at this moment I do not know that there are. Today's graduates are going to find it a good deal harder to find jobs than the graduates of my generation. In a sense this is a great advantage because it requires the young engineer at the very outset of his professional life to tackle a problem of the kind that may recur again and again as long as he works and lives. Today's graduates face a different environment which they are perfectly innocent of causing, and the problem will be to adjust themselves to it. I cannot emphasize too strongly the importance of cultivating a practical point of view toward it. There is no point in feeling resentful or sorry or helpless.

As creatures of the world we cannot live effectively unless we are in tune with our environment whatever it may be, and it is always changing.

In one form or another I presume most electrical-engineering graduates will seek their livelihood in the electrical industry. They have shown good sense in selecting this field. The very fact that the industry regulates our daily lives—and all one need do is glance at the skyline in the evening to have this vividly brought home—places a great responsibility upon those in it to continue further progress. Young electrical engineers are fortunate that it is an industry impelled by the spirit of progress; of service; that it is still permeated by enthusiam for the job it has to do and by an eagerness to find better ways of doing it.

We sometimes hear that there are too many lawyers, too many doctors, too many engineers. There may be too many lawyers, too many doctors—I don't know; but I do know there are not too many engineers. In the engineering profession as a whole there are roughly a quarter of a million engineers. Schools graduate 8,000 or 9,000 new engineers each year—barely enough to replace yearly losses due to mortality, changes, and other factors, which represents about four per cent. Increase in population also is a factor.

It would be idle for me to attempt to point out those things which on the surface all agree need continuing attention. Our best steam generating plants operate at an efficiency of 30 per cent; there are the problems of transmission and distribution—system stability under faulty conditions; new markets need to be developed; opportunities in the field of application are limitless.

One of the things that may surprise the young engineer is the extent to which nontechnical considerations enter into engineering problems. Let me cite a typical engineering problem in which broad social and human consideration played an important part. The problem consisted of moving an old eight-story telephone building to a new location without disturbing the functions normally performed therein, which included on the first floor business transactions with the public. The building weighed 11,000 tons, covered one-quarter acre of ground, and contained about 300 employees half of whom were women. It was moved 50 feet in one direction, then rotated through a 90-degree angle. The problem involved more than the maintenance of elevator, water, gas, light, and plumbing services; in order to obviate the possibility of panic among the employees, it was necessary to create a feeling of confidence in the safety of the operation.

Perhaps not all electrical-engineering graduates intend to be electrical engineers or even engineers at all; but whatever occupation they choose I think they will find their technical training of great value. They have learned to think quantitatively and to deal with facts. They have learned to tear their problem down to its elements and to draw sound conclusions from such data as are available. They have learned to be rigorously honest with their thinking. They should not think, therefore, that their technical preparation unsuits them for other things.

I want to say just a brief word about the national engineering societies and the American Institute of Electrical Engineers in particular. The vast and extensive current commercialism of new ideas brought about by research in both college and industry make it almost impossible to include in curricula much more than the basic fundamentals necessary to understand them. It becomes necessary, therefore, for men in industry to identify and associate themselves with such groups or agencies as have been created for purposes of professional advancement.

Our Institute was organized for the purpose of advancing the theory and practice of electrical engineering and its allied arts and sciences, and to maintain a high professional standing among our members. Our technical forums and publications are characterized by emphasis on scientific achievement, the development of technical proficiency, and concern for the public welfare wherever engineering knowledge and experience are involved.

In rendering service to the community, state, and nation, the societies are motivated by unselfish purposes and fairness in action both of which have found expression in codes of ethics or principles of professional conduct. Association with this professional group is characterized not only by the possession of a common technical knowledge and understanding, but also by an attitude of mind and character that implies conduct in keeping with the higher ideals of American social and industrial life.

Engineers, in order to keep pace with scientific and industrial advances, and in order to develop qualities of character and personality that make heart and mind sensitive to motives governing human behavior and their consequences as affecting others, should take advantage of the opportunities offered by membership in their national professional societies.

Finally, let me remind the young engineer that in his few years at college he has had time to do no more than make a fair beginning on his job of educating himself. He must then earn a living, and he may want to marry; certainly he will find many things interfering with his most important task, namely, the continuing of his education. But one thing is as sure as sunrise: If earning his living, poker games, movies, marrying and raising kids, or staying single and raising Cain, or anything else under the sun causes him to forget the fact that he somehow must continue to get an education, he is doomed. He will settle down into a more or less comfortable rut; he will do what other engineers direct him to do as long as he stays in the profession. A man may fail in college courses, and this usually eliminates him as a potential engineer; he may pass his college courses successfully, but within the next five years eliminate himself just as effectively.

Today's engineering graduates have the heritage of great schools, the background of sound training. They should hold fast to individual industry, effort, and integrity as these are the most cherished possessions of this nation of ours. These principles must prevail, and young engineers must safeguard them for the generations to come.

The road of tomorrow is challenging—the opportunities plentiful—the rewards great. "There is no failure except in no longer trying."

News
Of Institute and Related Activities

1938 Summer Convention Program Completed

THE annual summer convention of the Institute to be held in Washington, D. C., June 20–24, 1938, offers many attractive features. The nation's capital is the center of scenic and historical interest and the summer convention committee has taken full cognizance of this fact in arranging an excellent program of trips, sports, and entertainment, the details of which were announced in ELECTRICAL ENGINEERING for May 1938, pages 221–4. Convention headquarters will be in the Mayflower Hotel.

BUSINESS AND TECHNICAL PROGRAM

In addition to the annual business meeting, conference of officers, delegates, and members, and a conference of vice-presidents, District secretaries, and counselor delegates, ten technical sessions, one general session, and six conference sessions will be held. The general session designed to interest many members has been scheduled on Wednesday morning without parallel sessions in order to give all an opportunity to attend. The features of this session are addresses by President W. H. Harrison, Doctor W. R. Gregg, chief of the Weather Bureau, and Colonel J. M. Johnson, assistant secretary of commerce. At the annual meeting, on Tuesday morning, Colonel Dan I. Sultan, engineer commissioner, District of Columbia, will give an address.

ENTERTAINMENT

The summer convention committee requests that tickets be secured early for the entertainment features in order that proper reservations may be made. These include the following:

Tuesday, June 21

Luncheon bridge—tickets not later than Monday, 6:00 p.m.

Country club dinner dance—tickets not later than Tuesday noon.

Wednesday, June 22

Tea at Burgundy Farm—tickets not later than Wednesday, 10:00 a.m.

Thursday, June 23

Dinner, Mayflower Hotel—tickets not later than Thursday, 10:00 a.m.

REGISTRATION

Members who will attend the convention and who have not registered in advance are urged to do so promptly by returning the addressed advance registration card received by mail. This will be helpful to the committees and will permit badges to be made ready in advance, thus avoiding congestion at the registration desk. Please register promptly upon arrival at the convention.

A registration fee of $2.00 will be charged all nonmembers, except Enrolled Students, and the immediate families of members.

HOTEL RESERVATIONS

If you have not already made a hotel reservation, please do so, as the committee has urged that this be done well in advance. For a list of the principal hotels in Washington, D. C., and rates, as well as information regarding the Mayflower Hotel, convention headquarters, see ELECTRICAL ENGINEERING for May, pages 221 and 224.

RULES ON PRESENTING AND DISCUSSING PAPERS

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, ten minutes being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is opened for general discussion. Usually five minutes is allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser should step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for

AIEE New York Section Visits Pittsfield, Mass.

CHAIRMAN Aram Boyajian (A'18, F'26) *left*, of the AIEE Pittsfield Section, shook hands with Chairman K. F. Bellows (A'30, M'38) of the power group of the New York Section on April 21, 1938, when nearly 200 members traveled by special train to Pittsfield to visit the plastics and transformer and capacitor plants of the General Electric Company. H. H. Barnes (A'00, F'13) commercial vice-president of the General Electric Company, New York, N. Y., may be seen to the left of Mr. Boyajian. High light of the trip was a demonstration of artificial lightning under the direction of K. B. McEachron (A'14, F'37, director). A 10,000,000-volt discharge of approximately 23,000 amperes jumping between electrodes 30 feet apart, splitting wood, and vaporizing wire, and a 1,000,000-volt three-phase 60-cycle colored arc between revolving pinwheels were shown.

Eastern Standard Time

Business and Technical Program of the Summer

Photo-offset copies of authors' manuscripts, exclusive of addresses, may be obtained in advance of the convention by writing to the AIEE Order Department, 33 West 39th Street, New York, N. Y. If ordered by mail, price 10c per copy; if purchased at Institute headquarters or at the convention, price 5c per copy. Coupon books in $1.00 and $5.00 denominations are available for those who wish to avoid remittance by check or otherwise. Most of the papers ultimately will be published in Electrical Engineering or the Transactions.

Monday, June 20

9:00 a.m.—Registration

10:00 a.m.—Conference of Officers, Delegates, and Members

11:00 a.m.—Separate Conferences

(*a*) Section delegates.
(*b*) Student Branch counselors.

2:00 p.m.—Conference of Officers, Delegates, and Members (continued)

Tuesday, June 21

9:30 a.m.—Annual Meeting

Address of welcome by **Doctor William McClellan**, honorary chairman.

Annual report of board of directors, in abstract, by **H. H. Henline**, national secretary.

Report of national treasurer.

Report of committee of tellers on (*a*) constitutional amendments, and (*b*) election of officers.

Introduction of and response from president-elect.

Presentation of Institute prizes for papers.

Presentation of Lamme Medal to Doctor R. E. Doherty.

Address: Municipal Planning in Washington, **Colonel Dan I. Sultan**, engineer commissioner, District of Columbia.

2:00 p.m.—Power Transmission and Distribution

Traveling Waves Initiated by Switching, **L. V Bewley**, General Electric Company.

Application of Large Phase-Shifting Transformer on an Interconnected System Loop, **W. J. Lyman**, Duquesne Light Company, and **J. R. North**, Commonwealth and Southern Corporation.

Tests on Oil-Impregnated Paper—III—Fluid Flow, **H. H. Race**, General Electric Company.

Field Testing of Bushings and Transformer Insulation by the Power Factor Method, **I. W. Gross**, American Gas and Electric Service Corporation.

Flashover Characteristics of Transformer Condenser Bushings, **H. L. Cole**, Westinghouse Electric and Manufacturing Company.

Reactance of Square Tubular Busbars, **H. B. Dwight** and **T. K. Wang**, Massachusetts Institute of Technology.

2:00 p.m.—Communication

Analysis and Design of Harmonic Generators, **F. E. Terman**, Stanford University.

A Symbolic Analysis of Relay and Switching Circuits, **C. E. Shannon**, Massachusetts Institute of Technology.

Instruments for the New Telephone Sets, **W. C. Jones**, Bell Telephone Laboratories, Inc.

Transmission Features of the New Telephone Sets, **A. H. Inglis**, Bell Telephone Laboratories, Inc.

Presentation by title:

Transmission Theory of Spherical Waves, **S. A. Schelkunoff**, Bell Telephone Laboratories, Inc.

2:00 p.m.—Symposium on Correlation of Mathematics and Physics With Electrical Engineering Subjects

The Co-ordination of Mathematics and Physics With Electrical Engineering Subjects, **W. A. Curry**, Columbia University.

A Course to Develop Facility in the Use of Mathematics and Physics in the Solution of Engineering Problems, **B. R. Teare, Jr.**, Yale University.

Co-ordination of Physics With Electrical Engineering, **J. M. Bryant**, University of Minnesota.

Co-ordination of Mathematics and Physics With Electrical Engineering Subjects, **T. H. Morgan**, Worcester Polytechnic Institute.

Mathematics and Physics in Engineering, **M. G. Malti**, Cornell University.

2:00 p.m.—Conference on Machines in Mathematical Analysis

Wednesday, June 22

9:30 a.m.—General Session

(President W. H. Harrison, presiding)

Address of the president.

Address: Progress in Weather Forecasting, **Doctor W. R. Gregg**, chief of the Weather Bureau.

Address: The Present and Future of Commercial Aviation, **Colonel J. M. Johnson**, assistant secretary of commerce.

Thursday, June 23

9:30 a.m.—Fault Interruption—I

The Current-Limiting Power Fuse, **D. C. Prince** and **E. A. Williams, Jr.**, General Electric Company.

A New Multi-Break Interrupter for Fast-Clearing Oil Circuit Breakers, **R. M. Spurck** and **H. E. Strang**, General Electric Company.

Tests on and Performance of a High-Speed Multi-Break 138-Kv Oil Circuit Breaker, **Philip Sporn** and **H. P. St. Clair**, American Gas and Electric Service Corporation.

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publication must be submitted, typed double spaced, in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters, 33 West 39th St., New York, N. Y., on or before July 8, 1938.

Thomson Papers Being Collected

Because of his long period of membership and interest in the American Philosophical Society, the many papers, manuscript and printed, accumulated by the late Doctor Elihu Thomson are being collected and will be housed permanently by the society. Doctor Thomson was a charter member of the AIEE and its fifth president (1889–90); he was elected an Honorary Member in 1928. According to a recent announcement, the society already has collected about 2,000 pieces of correspondence, five volumes of Doctor Thomson's manuscript comments on his numerous patents, an almost complete set of his many articles contributed to scientific periodicals, a number of letter-books containing his correspondence during the early days of the General Electric Company and its forerunners, and other miscellaneous items.

In order to make the collection as complete as possible, the society has asked the many organizations of which Doctor Thomson was a member to notify their memberships of this project in the hope that thereby many scattered pieces of Thomsoniana might be added to the collection. The society will be very glad to accept copies of material with which original owners may be loath to part. The American Philosophical Society may be addressed at 222 Drexel Building, Philadelphia, Pa.

The General Electric Company also has announced that the office Doctor Thomson occupied for nearly 30 years in the old administration building of the company's West Lynn (Mass.) Works will be maintained as a museum containing historical material associated with his career. Among other things, the company plans to exhibit in this museum models of many of his numerous inventions.

Pacific Coast Program Nearing Completion

General arrangements for the 1938 AIEE Pacific Coast convention to be held in Portland, Ore., are now practically complete, according to General Chairman E. F. Pearson. The Multnomah Hotel has been selected as convention headquarters. As previously announced, the dates for this convention, August 9–12, have been selected to encourage members and their friends to combine their vacation trips with attendance at the convention. At this time the scenic beauty of Oregon is usually at

Convention, Washington, D. C., June 20–24

Eastern Standard Time

Deion Air Circuit Breakers for A-C Feeder, Motor Starting and Station Auxiliary Service, **R. C. Dickinson**, Westinghouse Electric and Manufacturing Company.

Enclosed Low-Voltage Deion Air Circuit Breaker of High Interrupting Capacity, **Jerome Sandin**, Westinghouse Electric and Manufacturing Company.

9:30 a.m.—Electrical Machinery

Double Line-to-Neutral Short Circuit of an Alternator, **James B. Smith**, Factory Mutual Fire Insurance Company, and **C. N. Weygandt**, University of Pennsylvania.
EE, September 1937, pages 1149–55

An Analysis of the Induction Machine, **H. C. Stanley**, American Gas and Electric Service Corporation.

Amplitudes of the Magnetomotive-Force Harmonics for Fractional Slot Windings—I, **J. F. Calvert**, Iowa State College.

The Cause and Elimination of Noise in Small Motors, **W. R. Appleman**, Marathon Electric Manufacturing Corporation.
EE, November 1937, pages 1359–67

The Wound-Core Distribution Transformer, **E. D. Treanor**, General Electric Company.

9:30 a.m.—Selected Subjects

The Economic Status of the Engineer, **R. W. Sorensen**, California Institute of Technology.

A Self-Checking System of Supervisory Control, **M. E. Reagan**, Westinghouse Electric and Manufacturing Company.

Application of Capacitance Potential Devices, **J. E. Clem**, General Electric Company.

Radio Influence Characteristics of Electrical Apparatus, **P. L. Bellaschi** and **C. V. Aggers**, Westinghouse Electric and Manufacturing Company.

Noise Co-ordination of Rural Power and Telephone Systems, **H. W. Wahlquist**, Edison Electric Institute, and **T. A. Taylor**, Bell Telephone Laboratories, Inc.

9:30 a.m.—Electronics and Basic Sciences

Positive-Grid Characteristics of Triodes, **R. W. Porter**, General Electric Company.

A Position Regulator for Paper Slitters, **F. H. Gulliksen**, Westinghouse Electric and Manufacturing Company.

Combined Thyratron and Tachometer Speed Control of Small Motors, **A. J. Williams, Jr.**, Leeds and Northrup Company.

A Static Constant-Current Circuit, **C. M. Summers**, General Electric Company.

Presentations by title:

Graphical Field Plotting Methods in Engineering, **Hillel Poritsky**, General Electric Company.

Basic Equations for Electric and Sound Radiations, **L. Alan Hazeltine**, Stevens Institute of Technology.

12:30 p.m.—Board of Directors' Luncheon Meeting—Mayflower Hotel

3:00 p.m.—Conference of Vice-Presidents, District Secretaries, and Counselor Delegates

2:00 p.m.—Conference Sessions:

(*a*) Modernization of power plants.
(*b*) Electrical machinery.
(*c*) Electronics.
(*d*) Conference on definitions.

Friday, June 24

9:30 a.m.—Symposium on Fluorescent Lighting

The Fundamental Principles of Fluorescence, **G. R. Fonda**, General Electric Company.

Low-Voltage Fluorescent Lamps, **G. E. Inman** and **R. N. Thayer**, General Electric Company.

High-Voltage Advertising and Decorative Tube Lighting, **J. A. McDermott**, Claude Neon Lights, Inc.

Demonstration Lecture: Penny Wise Pound Foolish—How to Get the Most for Your Lighting Dollar, **A. L. Powell**, General Electric Company.

9:30 a.m.—Fault Interruption—II and Lightning Protection

Remote Control of Network Protectors, **W. R. Brownlee** and **W. E. Dent, Jr.**, Tennessee Electric Power Company.

System Analysis for Petersen Coil Application—Part I. Operating Features and Basic Calculations—Part II. System Analysis and Computations, **W. C. Champe** and **F. von Voigtlander**, The Commonwealth and Southern Corporation.

Lightning Protection of 22-Kv Substations, **E. R. Whitehead**, Duquesne Light Company.

Line-Type Lightning-Arrester Performance Data, Lightning arrester subcommittee.

9:30 a.m.—Instruments and Measurements

A Memory Attachment for Oscilloscopes, **W. E. Pakala**, Westinghouse Electric and Manufacturing Company.

Absolute Power Factor of Air Capacitors, **W. B. Kouwenhoven** and **E. L. Lotz**, The Johns Hopkins University.

The Electric Strain Gauge, **M. A. Rusher** and **A. V. Mershon**, General Electric Company.

9:30 a.m.—Conference on Power Requirements in Electrochemical and Allied Industries

Address: Power Requirements in the Electrochemical, Electrometallurgical, and Allied Industries, **A. V. Alfriend, Jr.**, Federal Power Commission.

Discussion by: **M. E. Stone**, United Engineering and Foundry Company, Ltd.; **E. G. Merrick**, General Electric Company; **Herbert Speight**, Westinghouse Electric and Manufacturing Company.

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its best. Details of the program will be announced in the July issue.

Several excellent inspection trips have been arranged, including one to the Bonneville hydroelectric development, which will be completed prior to the convention, and another to the new Timberline Lodge on Mount Hood. The annual golf tournament will be played on Oswego Lake Country Club course, which is considered one of the finest of the Northwest.

Student Conference Held by North Central District

The 11th annual conference of Student Branches of the AIEE North Central District, held at the University of Nebraska, Lincoln, April 22–23, attracted 123 students in electrical engineering, AIEE Section and District officers, and guests. Three guests from Kansas State College, Manhattan (AIEE South West District) were registered and representatives were sent from all of the nine Branches in the district:

Colorado State College of Agriculture and Mechanic Arts, Fort Collins.
University of Colorado, Boulder.
University of Denver, Denver, Colo.
North Dakota State College, Fargo.
University of North Dakota, Grand Forks.
South Dakota State College, Brookings.
South Dakota State School of Mines, Rapid City.
University of Wyoming, Laramie.
University of Nebraska, Lincoln.

With B. J. Dalton, chairman of the University of Nebraska Branch, presiding, the morning session on April 22 was opened with an address of welcome by O. J. Ferguson (A'05, F'13) dean of the college of engineering of the University of Nebraska. L. N. McClellan (A'14, M'26) chief electrical engineer of the United States Bureau of Reclamation, Denver, Colo., and vice-president of the AIEE made an appropriate response.

After Mr. McClellan's talk the first technical session was convened with Eugene Jackson, chairman of the South Dakota State College Branch, presiding. The following papers were presented:

Theory and Application of the Thyratron-Controlled Stroboscope, **M. E. Mohr**, University of Nebraska.

Hyper-Frequency Wave Guides, **Eugene McFall**, University of Colorado.

Electromechanical Recording and Reproduction of Sound by the Disk Method, **Elmer W. Everson**, University of North Dakota.

Following discussion of the papers, I. M. Ellestad (A'24) transmission engineer of the Northwestern Bell Telephone Company, Omaha, Nebr., delivered an address entitled "Application of Newly Developed Cold-Cathode Discharge Tube to Telephone and Industrial Control."

With R. H. Payne, chairman of the Colorado State College Branch, presiding, the following papers were presented and discussed at the afternoon technical session:

The Electrolytic Condenser and its Development, **Carl Cadwell**, University of Wyoming.

THE USES OF ELECTRICITY IN MEDICAL QUACKERY, **John Herron,** South Dakota State College.

THE EFFICIENCY OF SMALL ELECTRIC MOTORS, **John L. C. Lof,** University of Denver.

Elmer Maul, chairman of the University of Colorado Branch, presided over the third technical session, at which the following papers were presented and discussed:

THE PIEZOELECTRIC EFFECT, **William Kossila,** North Dakota State College.

AUTOMOBILE HEAD LIGHTING AS IT IS AND AS IT MIGHT BE, **J. C. Smith,** South Dakota State School of Mines.

At the convention banquet, held on Friday evening, the principal address was delivered by R. M. Armstrong, of the Nebraska Unicameral Legislature. John L. C. Lof, of the University of Denver, won first prize for his paper and honorable mention was given to the paper by M. E. Mohr, of the University of Nebraska.

Following the banquet a business session of the Student Branch counselors was held. The University of Wyoming, Laramie, was selected as the site of the next Branch conference, with the dates established as April 21–22, 1939.

North West District Executive Committee Meets

The annual meeting of the executive committee of the Institute's North West District was held at Seattle, Washington, on April 19, 1938. The following members were present:

- C. E. Rogers, vice-president, AIEE, presiding
- S. E. Caldwell, secretary, North West District
- W. A. Boyer, vice-chairman, Montana Section
- C. C. Boozier, chairman, Portland Section
- C. H. Hoge, chairman, Seattle Section
- M. F. Hatch, chairman, Spokane Section
- C. A. Wolfrom, chairman, Utah Section
- A. L. Taylor, chairman, District committee on student activities, University of Utah, Salt Lake City
- John Bankus, vice-chairman, national membership committee
- L. R. Gamble of Spokane, nominee for vice-president, was present by invitation

Section reports indicated a very active interest in Institute activities throughout the District. The co-operation between Sections of the North West and Pacific Districts in arranging program schedules to fit itineraries of visiting engineers has made it possible for the Sections to have some exceedingly interesting and well attended meetings. Technical groups organized in the Portland and Seattle Sections have proved a material help in stimulating interest and getting new members. The group meetings have provided an excellent place for the interchange of ideas and a greater opportunity for the younger members to take part in Section activities. Vice-President Rogers pointed out that each Section could employ this idea to greater advantage by organizing additional technical groups in the larger outlying communities of its territory and thereby stimulate and hold the interest of members that would otherwise not be able to participate in any Section activities.

The District has shown a substantial increase in membership during the past year. Some of the Section membership committees obtained good results from return postal cards sent out to members requesting names of prospects. Members who had been dropped because of delinquent dues were, in a number of cases, induced to rejoin by paying back dues during the current year, for which limited Section privileges were accorded, and then to submit their application for reinstatement at the beginning of the next fiscal year. The suggestion was made that a faculty member from each college having a Student Branch, preferably the counselor, should be a member of his Section's membership committee in order to maintain closer contact with student members eligible for transfer to associate grade.

C. C. Boozier, chairman of the Portland Section, reported that the plans for the 1938 Pacific Coast convention to be held in Portland, Ore., August 9–12 were 100 per cent complete, that a full program of technical papers, inspection and scenic trips, sports, and entertainment had been planned, and that the date had been advanced to early in August in order that all who might desire could plan their vacation to coincide with the convention.

A resolution was adopted by the District executive committee expressing, upon behalf of the membership, its deepest regret over the death of Professor Thaler and its most sincere appreciation of his long and continued service and contributions to the Institute's activities and a copy of the resolution was transmitted to Professor Thaler's family.

At the close of the meeting the members of the committee extended to Vice-President Rogers a vote of appreciation for his active interest, counsel, and assistance during the past two years and for his efforts in procuring outstanding engineers as speakers for the Sections.

AIEE National Prize Awards Announced for 1937 Papers

THE committee on award of Institute prizes has announced the award of three national prizes for papers presented during the calendar year 1937. In two classifications, because of the small number of eligible papers, no awards were made. Presentation of the prizes will be made during the AIEE summer convention at Washington, D. C., June 20–24, 1938. The committee consists of H. S. Osborne (A'10, F'21) *chairman*, J. W. Barker (M'26, F'30) W. B. Kouwenhoven (A'06, F'34) and I. Melville Stein (A'18, M'27).

Rules governing the award of prizes were published in ELECTRICAL ENGINEERING for April 1937, page 492. The following awards of national prizes for 1937 papers were made after consideration of all the eligible papers:

BEST PAPERS

Best Paper in Engineering Practice. This prize was awarded to J. W. Dawson (M'35) for his paper "New Developments in Ignitron Welding Control," published in ELECTRICAL ENGINEERING for December 1936, pages 1371–8, and discussed at the winter convention, New York, N. Y., January 25–29, 1937.

Honorable mention was made of the following papers: "Approximating Potier Reactance" by Sterling Beckwith (A'34) discussed at the summer convention, Milwaukee, Wis., June 21–25, 1937, and published in ELECTRICAL ENGINEERING for July 1937, pages 813–18; "Development of a Modern Watt-Hour Meter" by I. F. Kinnard (A'21, M'28) and H. E. Trekell (A'35) published in ELECTRICAL ENGINEERING for January 1937, pages 172–9, and discussed at the winter convention, New York, N. Y., January 25–29, 1937; "Switchboards for Boulder Power Plant" by L. N. McClellan (A'14, M'26) A. J. A. Peterson (A'16, M'30) and C. P. Garman (A'23, M'26) published in ELECTRICAL ENGINEERING for February 1937, pages 224–36, and discussed at the summer convention, Milwaukee, Wis., June 21–25, 1937; and "System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods," by R. D. Evans (A'21, M'26) and A. C. Monteith (A'25) published in ELECTRICAL ENGINEERING for June 1937, pages 695–705, and discussed at the summer convention, Milwaukee, Wis., June 21–25, 1937.

Best Paper in Theory and Research. This prize was awarded to C. L. Dawes (A'12, F'35) and Reuben Reiter (A'36) for their paper "Electrical Characteristics of Suspension-Insulator Units," published in ELECTRICAL ENGINEERING for January 1937, pages 59–66, and discussed at the summer convention, Milwaukee, Wis., June 21–25, 1937.

Honorable mention was made of the following papers: "Dyadic Algebra Applied to Three-Phase Circuits," by A. P-T. Sah (A'35, M'36) published in ELECTRICAL ENGINEERING for August 1936, pages 876–82, and discussed at the winter convention, New York, N. Y., January 25–29, 1937; "Magnetic Generation of a Group of Harmonics," by Eugene Peterson (M'26), J. M. Manley and L. R. Wrathall, published in ELECTRICAL ENGINEERING for August 1937, pages 995–1001, and discussed at the Pacific Coast convention, Spokane, Wash., August 30–September 3, 1937; "Properties of Saturants for Paper-Insulated Cables," by G. M. L. Sommerman (A'31, M'37) published in ELECTRICAL ENGINEERING for May 1937, pages 566–76, and discussed at the summer convention, Milwaukee, Wis., June 21–25, 1937; and "Short-Time Spark-Over of Gaps," by J. H. Hagenguth (A'28) published in ELECTRICAL ENGINEERING for January 1937, pages 67–76, and discussed at the winter convention, New York, N. Y., January 25–29, 1937.

Best Paper in Public Relations and Education. Because only one paper in this classification was presented during the year, the committee made no award, and this paper, together with two papers in this classification from 1936, will be held over for consideration for a future award in this classification.

INITIAL PAPER

Prize for initial paper was awarded to H. R. Reed (A'28, M'34) and R. J. W. Koopman (A'36) for their paper "Induction Motors on Unblanced Voltages," published in ELECTRICAL ENGINEERING for November 1936, pages 1206–13, and discussed at the winter convention, New York, N. Y., January 25–29, 1937.

Honorable mention was made of the following papers: "A Review of Overhead Secondary Distribution," by W. P. Holben (A'20, M'27), published in ELECTRICAL ENGINEERING for January 1937, pages 114–22 and 189, and discussed at the winter convention, New York, N. Y., January 25–29, 1937; and "Fundamental Concepts of Synchronous-Machine Reactances," by B. R. Prentice (A'35), presented at the summer convention, Milwaukee, Wis., June 21–25, 1937, and published in AIEE TRANSACTIONS, volume 56, 1937, pages 1–21 of Supplement.

BRANCH PAPER

Only three papers eligible for this award were submitted for consideration, and therfore no award was made this year. The committee points out that an inadequate group of papers was submitted despite the fact that more than 1,100 student talks were presented at Branch meetings during the year.

District prize awards for 1937 papers will be announced in future issues as this information is made available.

Dates Selected for Southern District Meeting

November 28–30 has been chosen as the time for the AIEE Southern District meeting to be held this year at Miami, Fla. This is one of the actions taken by the District meeting committee when it met April 21 in Jacksonville to discuss preliminary plans.

Headquarters for the meeting will be at the Miami Biltmore Hotel. In addition to ample facilities for all convention activities, the hotel and its grounds include an 18-hole golf course, swimming pool, tennis courts, and other recreational facilities, as well as access to beach and fishing accommodations.

1938 Washington Award Presented to F. B. Jewett

For "inspiring and directing scientific research leading to improvements in the art of communication," the Washington Award for 1938 was presented to F. B. Jewett (A'03, F'12, past-president) at Chicago, Ill., on May 5, 1938, by L. R. Howson, president of the Western Society of Engineers, at a dinner held by the Washington Award Commission. Announcement of the selection of Doctor Jewett as 1938 recipient and a brief history of the award, which is given by a commission composed of representatives of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Mechanical Engineers, AIEE, and Western Society of Engineers, were published in ELECTRICAL ENGINEERING for February 1938, pages 78–9.

Following the presentation ceremony, Doctor Jewett delivered an address on "The Engineer and Current Trends in Economic Thought." C. H. MacDowell, chairman of the commission, presided.

Future AIEE Meetings

Summer Convention
Washington, D. C., June 20–24, 1938

Pacific Coast Convention
Portland, Ore., August 9–12, 1938

Southern District Meeting
Miami, Fla., November 28–30, 1938

Winter Convention
New York, N. Y., January 23–27, 1939

South West District Meeting
Houston, Texas, Spring, 1939

Section and Branch Activities Annual Report for 1937–38

THE following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1938. Similar information for three preceding fiscal years appeared in ELECTRICAL ENGINEERING for June 1937, pages 762–5; June 1936, pages 752–4; and June 1935, pages 674–5.

The names of present members of the Sections committee and the committee on Student Branches, which supervise these two important divisions of Institute activities covered by this report, are: Sections—W. H. Timbie, *chairman*, M. S. Coover, W. M. Dann, O. W. Holden, E. T. Mahood, H. H. Race, I. M. Stein, C. S. Thorn, and, *ex-officio*, the chairmen of all Sections of the Institute. Student Branches—F. Ellis Johnson, *chairman*, Edward Bennett, E. E. Dreese, O. E. Edison, O. W.

Table I. Section Meetings Held During Year Ending April 30, 1938

Section	AIEE Members		Meetings During Year		Average Attendance as Per Cent of Membership, August 1937
	August 1936	August 1937	Number	Average Attendance	
Akron	67	63	8	68	108
Alabama	42	48	5	137	285
Baltimore	174	188	8	137	73
Boston	386	409	8	401	98
Central Indiana	116	135	7	127	94
Chicago	603	674	11	265	39
Power group			5	149	
Industrial group			3	93	
Cincinnati	159	175	10	136	78
Cleveland	245	285	8	166	58
Motors and control group			3	46	
Electronics group			2	53	
Columbus	63	79	5	50	63
Connecticut	267	266	9	390	147
Dallas	89	101	10	177	176
Denver	132	160	7	263	164
Detroit-Ann Arbor	320	353	9	577	163
East Tennessee	49	76	9	110	145
Erie	52	63	7	192	305
Florida	60	66	3	80	121
Fort Wayne	64	86	9	77	90
Georgia	72	83	10	136	164
Houston	75	89	12	140	157
Iowa	56	53	7	105	198
Ithaca	54	54	10	51	94
Kansas City	148	122	9	125	102
Lehigh Valley	184	197	9	176	89
Los Angeles	440	470	10	434	92
Louisville	50	49	8	93	190
Lynn	120	128	11	518	405
Technical lectures			5	290	
Madison	48	64	11	155	242
Memphis	33	53	11	47	89
Mexico	67	67	7	42	63
Milwaukee	208	268	11	211	79
Minnesota	72	88	6	73	83
Power committee			3	39	
Montana	38	39	8	215	551
Muscle Shoals*		33	7	156	473
Nebraska	56	55	8	63	115
New Orleans	50	64	8	81	127
New York	3,036	3,308	4	563	17
Power group			7	281	
Communication group			5	314	
Transportation group			3	133	
Illumination group			4	506	
Electrophysics group			2	325	
Niagara Frontier	208	218	8	307	141
North Carolina	83	77	3	96	125
Oklahoma City	120	97	9	113	116
Philadelphia	550	571	8	191	33
Pittsburgh	411	464	8	224	48
Pittsfield	121	150	11	855	570
Colloquium series			4	42	
Portland	110	119	11	195	164
Transmission and distribution committee			6	30	
Communication committee			4	22	
Providence	82	93	7	83	89
Rochester	80	92	15	116	126
Communication group			2	9	
Power group			2	23	
St. Louis	201	240	8	239	100
San Antonio	29	35	7	40	114
San Francisco	401	442	8	205	46
Special technical meetings			7	373	
Saskatchewan	25	25	9	48	192
Schenectady	367	397	9	319	80
Technical discussion meetings			4		
Seattle	146	144	11	199	138
Power group			5	42	
Communication and electronics technical group			5	61	
Sharon	62	77	9	79	103
Spokane	48	55	8	265	482
Springfield	68	68	9	91	134
Syracuse	71	73	3	230	315
Toledo	66	78	8	120	154
Toronto	293	309	13	151	49
Discussion group			1	111	
Tulsa†		61	6	132	216
Urbana	36	58	5	232	400
Utah	41	59	9	198	336
Vancouver	97	99	12	53	54
Virginia	90	92	2	60	65
Washington	258	256	8	137	54
Special technical meeting			1	108	
Wichita‡		27	9	30	111
Worcester	63	67	8	92	137
Total..65	11,822	13,054			

Total number of meetings.............. 624
Total attendance..........................110,148

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* Organized February 18, 1938—previously power group, Alabama Section.

† Organized September 16, 1937.

‡ Organized October 18, 1937.

Table II. Section Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30		
	1936	1937	1938
Number of Sections	61	62	65
Number of meetings held	540	621	624
Average number of meetings	8.9	10.0	9.6
Total attendance	85,501	74,950	110,148
Average attendance per meeting	158	121	177

Eshbach, T. W. Fitzgerald, E. A. Loew, Charles F. Scott, R. W. Sorensen, and, *ex-officio*, all Student Branch counselors.

SECTION ACTIVITIES

Three new Sections were organized during the year: Wichita in September, Tulsa in October, and Muscle Shoals in February. These brought the total number of Sections to 65, and each of the new Sections carried on normal amounts of activity. The name of the Atlanta Section was changed to "Georgia Section," and it was granted the entire state as its territory.

The total number of Section meetings reported was 624, as compared with 621 for the preceding year, which had far exceeded the number for any previous year. Many Sections continued to show keen interest in technical groups, special technical meetings, technical committees, etc.

President Harrison visited nearly 30 Sections, and his addresses were deeply appreciated. He will visit a few others in May and June.

One of the outstanding features of Section activities was a lecture-demonstration showing the application of scientific knowledge to modern communication given by Doctor J. O. Perrine, associate editor, *Bell System Technical Journal*, at meetings of nearly one-third of the Sections, with an average attendance of more than 1,000.

The New York Section organized an electrophysics group, and the activities of the other four groups were continued.

An investigation made by the Washington Section indicated sufficient interest to justify holding certain meetings of a more technical type. The executive committee authorized two such meetings, and the first, on electronics, was held on February 23 with an attendance of 108.

The Connecticut Section sent postal cards to its members in October requesting expressions of their choices among several groups of subjects and indications of their preferences as to type of treatment: highly technical, moderately technical, or descriptive.

The Schenectady Section distributed a questionnaire, in November, inviting its members to choose 5 subjects for technical discussion meetings from a list of 15 mentioned, and left a blank for other subjects.

The New Orleans Section had an interesting meeting devoted to a round table discussion of topics selected from ELECTRICAL ENGINEERING.

The Pittsfield Section devoted a meeting of its colloquium series to discussion of eight papers presented at the 1938 winter convention.

The Lynn Section held two local conventions, one for technical-papers competition, and the other for popular-papers competition. The prizes in each case were $15, $10, and $5.

In order to secure the views of its mem-

Table III. Branch Meetings Held During Year Ending April 30, 1937

Branch	Meetings During Year		
	Number	Average Attendance	Approximate Number of Talks by Students
Akron, University of	8	17	
Alabama Polytechnic Institute	12	64	5
Alabama, University of	18	16	4
Arizona, University of	28	11	18
Arkansas, University of	18	37	15
Armour Institute of Technology	13	41	8
British Columbia, University of	15	29	16
Brooklyn, Polytechnic Institute of	10	51	4
Brown University	12	37	3
Bucknell University	14	13	7
California Institute of Technology	13	24	3
California, University of	18	62	
Carnegie Institute of Technology	31	45	25
Case School of Applied Science	26	55	21
Catholic University of America	5	10	4
Cincinnati, University of	6	37	7
Clarkson College of Technology	13	149	1
Clemson Agricultural College	5	28	9
Colorado State Agricultural College	5	13	5
Colorado, University of	11	55	10
Columbia University	3	22	1
Cooper Union			
Day division	12	24	7
Evening division	5	12	1
Cornell University	3	17	
Denver, University of	14	42	1
Detroit, University of	7	31	
Drexel Institute	21	33	4
Duke University	9	26	11
Florida, University of	13	28	7
George Washington University	7	28	3
Georgia School of Technology	5	46	
Harvard University	3	28	
Idaho, University of	10	39	3
Illinois, University of	11	141	
Iowa State College	16	84	3
Iowa, University of	22	51	19
Johns Hopkins University	17	24	13
Kansas State College	20	134	36
Kansas, University of	9	125	3
Kentucky, University of	15	89	4
Lafayette College	6	20	4
Lehigh University	3	75	
Lewis Institute	13	35	
Louisiana State University	17	22	6
Louisville, University of			
Maine, University of	6	21	5
Marquette University	9	39	1
Maryland, University of	10	29	12
Massachusetts Institute of Technology	10	76	3
Michigan College of Mining & Technology	12	42	9
Michigan State College	16	35	7
Michigan, University of	8	64	3
Milwaukee School of Engineering	8	48	1
Minnesota, University of	12	63	7
Mississippi State College	9	35	4
Missouri School of Mines & Metallurgy	9	38	7
Missouri, University of	10	60	3
Montana State College	25	28	54
Nebraska, University of	15	49	10
Nevada, University of	9	31	
Newark College of Engineering	7	36	9
New Hampshire, University of	10	48	
New Mexico, University of	5	14	3
New York, College of the City of			
Day division	17	71	3
Evening division	5	11	1
New York University			
Day division	4	19	1
Evening division			
North Carolina State College	16	32	9
North Carolina, Unversity of	6	10	7
North Dakota State College	7	13	2
North Dakota, University of	14	13	8
Northeastern University	13	51	
Northwestern University*	8	31	8
Notre Dame, University of	1	37	1
Ohio Northern University	8		9
Ohio State University	11	42	7
Ohio University	13	17	5
Oklahoma A. & M. College	11	40	12
Oklahoma, University of	9	40	10
Oregon State College	12	159	
Pennsylvania State College	9	34	
Pennsylvania, University of	2	17	
Pittsburgh, University of	24	84	17
Porto Rico, University of			
Pratt Institute	22	43	8
Princeton University	6	60	3
Purdue University	12	237	6
Rensselaer Polytechnic Institute	6	128	6
Rhode Island State College	10	38	2
Rice Institute	14	19	7
Rose Polytechnic Institute	5	29	5
Rutgers University	6	28	
Santa Clara, University of	11	18	10
South Carolina, University of	8	9	1
South Dakota State College	13	19	9
South Dakota State School of Mines	7	24	3
Southern California, University of	12	18	8
Southern Methodist University	7	36	8
Stanford University	7	26	
Stevens Institute of Technology	5	12	
Swarthmore College	2	56	
Syracuse University	33	59	12
Tennessee, University of	8	100	1
Texas A. & M. College	12	68	5
Texas Technological College	14	18	3
Texas, University of	3	21	4
Tufts College	5	24	1
Tulane University	5	30	8
Union College	7	36	3
Utah, University of	9	22	12
Vermont, University of	18	15	10
Villanova College	11	26	15
Virginia Military Institute	14	85	10
Virginia Polytechnic Institute	24	54	34
Virginia, University of	6	19	4
Washington, State College of	11	38	5
Washington, University of	11	62	9
Washington University	11	46	
West Virginia University	19	38	143
Wisconsin, University of	6	37	
Worcester Polytechnic Institute	3	35	5
Wyoming, University of	17	11	4
Yale University	12	21	4
Total..120			897

Total number of meetings..............1,334
Total attendance......................60,446

*Authorized by board of directors January 26, 1937, organized November 11, 1937.

Table IV. Branch Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30		
	1936	1937	1938
Number of Branches	118	119	120
Number of meetings held	1,045	1,363	1,334
Average number of meetings	8.9	11.5	11.1
Total attendance	45,304	46,121	60,446
Average attendance per meeting	43	33.8	45.3
Number of student talks	772	1,130	897

Table V. Conferences on Student Activities

District or Section	Location	Date
1	Buffalo, N. Y. (North Eastern District meeting)	5/7/37
2	Akron, Ohio (Middle Eastern District meeting)	10/15/37
8 & 9, University of British Columbia	Spokane, Wash. (Pacific Coast convention)	9/1/37
4	Virginia Military Institute, Lexington	3/25/38
5	University of Illinois, Urbana	4/22/38
6	University of Nebraska, Lincoln	4/22/38

Table VI. Student Conventions

Sponsored by District, Section, or Branch	Location	Date	Number of Student Papers
1	Buffalo, N. Y. (North Eastern District meeting)	5/7/37	8
8 & 9, University of British Columbia	Spokane, Wash. (Pacific Coast convention)	9/1–2/37	11
2	Akron, Ohio (Middle Eastern District meeting)	10/15/37	6
4	Virginia Military Institute, Lexington	3/25/38	6
Lehigh University	Lehigh University Bethlehem, Pa.	4/11/38	
University of Illinois	Urbana	4/23/38	4
6	University of Nebraska, Lincoln	4/22/38	8
New York Section	Newark College of Engineering, Newark, N. J.	4/28/38	5

bers on types of programs, papers, etc., the Houston Section had several brief talks on topics previously assigned given at a meeting in September. The announcement of its January meeting contained a request that members advise the secretary or chairman of their interest in any additional activities such as several which were mentioned.

The Cincinnati Section organized a study discussion group for consideration of social problems in which engineers should be of greater service. The earlier meetings were devoted to discussion of articles on social and economic subjects which recently appeared in ELECTRICAL ENGINEERING.

The Connecticut Section sent a questionnaire to its members in the fall to ascertain their preferences regarding types of educational courses. A course in electronics was given. The power group of the New York Section gave courses in electrical engineering and public speaking in the fall, and repeated them in the spring. The power group and the ASME metropolitan section gave courses in structural planning and design and engineering economics and practice in the fall, and again in the spring. The communication group of the New York Section gave a course in electronics. The Vancouver Section gave a course in electrical theory and engineering practice.

The Pittsfield and Schenectady Sections held their ninth annual competition in two joint meetings, one in each city, with three speakers representing each Section at each meeting. Prizes of $15 and $10 were awarded at each meeting.

The Seattle and Springfield Sections each held a prize-paper meeting with a prize of $25 for the best paper. The Portland Section held its annual competition with prizes of $15 and $10. Eight papers were presented. The power group of the New York Section held a volunteer-paper contest with prizes of $50 and $25.

The Sections which have been sponsoring student activities through the holding of joint meetings with Branches, or student conventions, continued the arrangements, with the usual keen interest and appreciation on the part of the students. Detailed information on such activities is given in table VII.

Table I contains tabular information on the meetings of all Sections and of their technical groups, technical committees, discussion groups, and other subdivisions.

Table II contains numerical information on Section meetings held during the past three fiscal years.

BRANCH ACTIVITIES

A new Branch organized at Northwestern University brought the total number to 120. A large majority of the Branches carried on normal amounts of activity. The total number of meetings reported was slightly below that for the preceding fiscal year, but was far larger than the total for any other year. The total number of student talks was below that for the preceding year, but larger than the totals for the fiscal years ending in 1935 and 1936, and smaller than the totals for the previous four years.

During the past fiscal year, 23 Branches held more than 15 meetings each, 59 held from 8 to 15, 27 held from 4 to 7, and 11 held fewer than 4 meetings.

Students continued their usual enthusiastic participation in national conventions and District meetings, and student sessions

Table VII. Section or Joint Section and Branch Meetings With Active Student Participation

Sections	Schools	Date	Student Talks	Attendance
Cincinnati	University of Cincinnati	5/4/37	7	125
Oklahoma City	Oklahoma A. & M. College, University of Oklahoma	5/14/37	6	112
Portland	Oregon State College	5/15/37	3	90
St. Louis	Missouri School of Mines & Met., University of Missouri, Washington University	5/21/37	6	85
Utah	University of Utah	5/24/37	3	50
Pittsburgh	Carnegie Institute of Technology, Pennsylvania State College, University of Pittsburgh, West Virginia University	1/11/38	3	285
Dallas	Southern Methodist University	1/26/38	4	105
Kansas City	University of Kansas	2/15/38	2	75
Vancouver	University of British Columbia	3/7/38	3	52
Philadelphia	Drexel Institute, University of Pennsylvania, Swarthmore College, Villanova College	3/15/38	4	125
Houston	Rice Institute, Texas A. & M. College	3/18/38	2	48
Iowa	Iowa State College, University of Iowa	4/5/38	9	109
Chicago	Armour Institute of Technology, Lewis Institute, Northwestern University	4/6/38	5	100
Washington	Catholic University of America, George Washington University, University of Maryland	4/12/38	3	70
Spokane	University of Idaho, Washington State College	4/15/38		100
Cleveland	Case School of Applied Science	4/21/38	2	158
San Francisco	University of California, University of Santa Clara, Stanford University	4/22/38	3	118
Totals—17 Sections, 35 Branches			65	1,807

were held as follows: North Eastern District meeting, Buffalo, N. Y., May 5–7, one session, eight papers; Pacific Coast convention, Spokane, Washington, August 31–September 3, two sessions, 11 papers; Middle Eastern District meeting, Akron, Ohio, October 13–15, one session, six papers.

The students also continued their participation in joint meetings with Sections, student conventions, etc. Comprehensive information on many phases of Branch activities appears in tables III to VII, inclusive.

The committee on safety, with the endorsement of the chairman of the committee on student Branches, suggested that each Branch have during the year "a paper dealing with some phase of the problem of the prevention of accidents or remedial measures after electrical shock." Such papers were presented at meetings of at least 24 Branches.

Of the 1,474 Enrolled Students whose terms expired on April 30, 1937, 703, or about 48 per cent, applied for admission as Associates. The corresponding figures last year were 1,253; 674; and about 54 per cent. The percentages for the preceding few years were about 50 per cent.

Shasta Dam New Construction Project

On June 1, 1937, bids were opened for Shasta Dam on the upper Sacramento River in California. With a concrete volume of 5,400,000 cubic yards and a height of 560 feet, the dam will exceed the 3,250,000-cubic-yard Boulder Dam and the 550-foot Grand Coulee Dam. Shasta Dam will be 14 miles north of Redding and five miles below the mouth of the Pit River. It is the key unit in the Central Valley irrigation and flood-control project of the United States Bureau of Reclamation, and will store water that will be used to replenish groundwater in the San Joaquin Valley and to check salt-water incursion from San Francisco Bay into the delta region of the San Joaquin and Sacramento Rivers.

A powerhouse at the dam will have initially four 70,000-kw 13,800-volt generators each connected to a 100,000-horsepower turbine operated under heads from 242 to 479 feet. The ultimate capacity is planned to be 350,000 kw. A transmission line will extend 200 miles south to the delta region.

It is estimated that a construction period of five years will be required.

Franklin Institute Dedicates Memorial; Presents Medals

In a three-day program at Philadelphia, Pa., May 19–21, 1937, of The Franklin Institute, formally dedicated "In Honor of Benjamin Franklin," a heroic white-marble statue of Franklin by James Earle Fraser was unveiled. The various medals awarded annually by the institute were presented to the 1938 recipients as one part of the program which included addresses by prominent speakers, conferring of honorary degrees by the University of Pennsylvania, a parade, and special museum exhibits.

William Frederick Durand, professor emeritus of mechanical engineering, Stanford University, and Charles A. Kraus, professor of chemistry and director of research in chemistry, Brown University, each received the Franklin Medal, highest award of The Franklin Institute, which is given annually "to those workers in physical science or technology, without regard to country, whose efforts have done most to advance a knowledge of physical science or its applications." Nine other medals also were presented to ten individuals (one post-humously) and two companies.

Among those delivering lectures on applied science was W. R. Whitney (A'01) vice-president in charge of research, General Electric Company, Schenectady, N. Y., who spoke on "It's Called Electricity." Herbert Hoover (HM'29) was the speaker at a banquet held on the final day of the program.

1938 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1939, may be submitted by any member in accordance with Section 1 of Article VI of the by-laws of the Lamme Medal committee, as quoted in the following:

> The committee shall cause to be published in one or more issues of Electrical Engineering, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specified specific information should be given regarding his individual contributions. Names of endorsers should be given as specified above.

The Lamme Medal, founded as a result of a bequest of the late Benjamin Garver Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company (deceased July 8, 1924), provides for the annual award by the Institute of a gold medal —together with bronze replica thereof— to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery"; and for the award of two such medals in some years if the accumulation of funds warrants.

The tenth (1937) Lamme Medal has been awarded to Doctor R. E. Doherty (A'16, M'27), president, Carnegie Institute of Technology, Pittsburgh, Pa., "for his extension of the theory of alternating current machinery, his skill in introducing that theory into practice, and his encouragement of young men to aspire to excellence in this field." Presentation will be made during the AIEE summer convention at Washington, D. C., June 20–24, 1938. A biographical sketch of Doctor Doherty appeared in Electrical Engineering for March 1938, page 141.

Membership—

Mr. Institute Member:

Do the men working for you or associated with you know that you belong to the Institute? Have you ever invited one of them to attend a Section meeting as your guest? Your associate would appreciate such an invitation and he might ask you some questions about the Institute and how to join it. If he does, don't worry about the details but introduce him to a member of the membership committee and then bring another guest to the next meeting.

The membership committee and the Institute will thank you if you find it possible to follow this suggestion.

Fred B. Doolittle

Vice-Chairman, District No. 8,
National Membership Committee

A membership proposal form appears on page 16 of the advertising section of this issue

"Research Day" in New England

A region-wide co-operative effort to stimulate greater use of research by New England industry for the continuous development of new products was made on May 20, 1937, when the New England Council, in co-operation with the Engineering Societies of New England, Inc., and eight New England colleges staged the first annual New England Research Day with meetings at Durham, N. H., Augusta, Me., Boston and Worcester, Mass., Providence R. I., and Hartford, Conn.

The all-day programs included visits to leading plant and institutional laboratories, luncheon and dinner meetings, and exhibits of new products developed by New England manufacturers through the use of research. Among speakers at the various meetings were K. T. Compton (F'31) and Vannevar Bush (A'15, F'24) of Massachusetts Institute of Technology. F. W. Bliss (A'30) president of the Engineering Societies of New England, Inc., in a joint statement with R. W. Sulloway, said, in part, "Research creates industry and develops new possibilities of employment. It widens the horizon of the manufacturer, discovers new and better production methods and equipment, makes possible the development of new products and the further development of old products, and brings prices and goods within the reach of more and more consumers . . . all of our industrialists, large and small, should realize the vital necessity of employing research methods."

Co-operating colleges were the University of Maine, University of New Hampshire, Massachusetts Institute of Technology, Harvard School of Engineering, Worcester Polytechnic Institute, Brown University, Connecticut State College, and Yale University.

Future Meetings of Other Societies

American Association for the Advancement of Science. Summer meeting, June 27–July 2, Ottawa, Can.

American Physical Society. 221st meeting, June 22–24, San Diego, Calif.
222d meeting, June 24–25, Toronto, Can.

American Society for Testing Materials. Annual meeting, June 27–July 1, Atlantic City, N. J.

American Society of Civil Engineers. Annual convention, July 20–22, Salt Lake City, Utah.

American Society of Heating and Ventilating Engineers. Semiannual meeting, June 20–22, Hot Springs, Va.

American Society of Mechanical Engineers. Semiannual meeting, June 20–24, St. Louis, Mo.

American Society of Refrigerating Engineers. Spring meeting, June 20–24, State College, Pa.

Canadian Electrical Association. Annual convention, June 22–24, Seigniory Club, Province of Quebec, Can.

Illuminating Engineering Society. Annual convention, August 29–September 1, Minneapolis, Minn.

Institute of Radio Engineers. Annual convention, June 16–18, New York, N. Y.

International Conference of Naval Architects and Marine Engineers. June 16–18, London, England.

International Engineering Congress. June 21–24, Glasgow, Scotland.

National Electrical Contractors Association. September 12–15, Detroit, Mich.

Society for the Promotion of Engineering Education. Annual meeting, June 27–30, College Station, Texas.

Society of Chemical Industry. Annual meeting, June 20–22, Ottawa, Can.

New Facilities for Scientific Activities

Office and laboratory space together with services and facilities as desired have been offered by Electrical Testing Laboratories, Inc., New York, N. Y., through a rental plan for any scientific, technical, trade, or institutional activity. The laboratories recently have acquired a larger building, adjacent to the quarters they have occupied since 1904, and space beyond their requirements is available for rental.

The facilities offered to tenants include a storeroom, comprehensive equipment of instruments, machine and carpenter shops, and photographic, photostatic, stenographic, mimeographing, accounting, and telephone and telephone-message services. Part or all of these may be had to meet the individual needs of tenants.

Steam Generating Stations. Recently published by *Science et Industrie*, Paris, France, a book entitled "L'Évolution Des Grandes Centrales Thermiques" outlines in some detail the evolution of large steam generating stations throughout the world. The book, which is in French, is divided into three parts: part I, which emphasizes principally French engineering practice, contains 11 papers on the design and operation of steam central stations, together with abstracts of five foreign papers; part II contains descriptions of large French central stations; and part III describes new equipment for central stations. Copies of the book may be obtained at a cost of 45 francs (in France 40 francs) from *Science et Industrie*, 29, Rue De Berri, Paris (8e) France.

ASHVE Announces Air-Conditioning Study

The 1938 program of research announced by the American Society of Heating and Ventilating Engineers lays renewed emphasis on the need for more highly organized and co-ordinated studies of the physiological aspects of air conditioning. W. L. Fleisher, chairman of the society's committee on research has outlined a long-range study designed to widen the industry's existing knowledge of problems vital to the progress of air conditioning. More than 50 scientists, physicians, surgeons, public health authorities, and engineers, will co-operate in the study.

One of the important phases of the research program will be a more extensive study of sensations of comfort experienced under varying artificial conditions of the atmosphere, especially in summer, and a comprehensive investigation of methods for cleaning the air of minute impurities by mechanical and electrical means. Possibilities in new methods of radiant heating in their effect on comfort also will be studied. The work will be carried out through several committees.

New Antenna for WGY

A new 625-foot radiator for WGY, radiobroadcasting station of the General Electric Company at Schenectady, N. Y., recently was placed in service with expectations of increased range. The trenches of the grounding system, which contains 14 miles of wire, may be seen in the view reproduced here. The tower, nine feet square, is guyed by eight lines broken by insulators into segments; its weight rests on a base insulator which was tested in the Bureau of Standards to withstand 2,000,000 pounds, or four times the normal load.

Baekeland to Receive Medal. Announcement has been made that Doctor Leo H. Baekeland, inventor of Bakelite, has been elected to receive the Messel Medal for 1938. This medal is awarded by the Society of Chemical Industry every two years for outstanding achievement in science. It was founded in 1922 in honor of Rudolph Messel, benefactor, one of the original members, and twice president of the Society of

Chemical Industry. The medal will be presented to Doctor Baekeland at the annual meeting of the society in Ottawa, Canada, on June 20, 1938.

American Engineering Council

AEC Holds First Forum in Philadelphia

Carrying out one of the first steps in its new program of activities (as reported in Electrical Engineering for May, pages 228–9) American Engineering Council held the first of its projected series of forums at the Engineers' Club of Philadelphia, Pa., May 13, 1938, devoted to the subject "Employment and the Engineer's Relation to It." The program was arranged in two sessions, one following a general luncheon gathering, and the other following dinner in the evening. The 125 engineers and others who were present for the afternoon session engaged so actively in discussion that the meeting finally had to be declared adjourned to enable the club staff to make ready for dinner. The complete program was as follows:

Afternoon Session

Chairman—William L. Batt, president, SKF Industries, Philadelphia; member, AEC executive committee.

1:00 Luncheon.

1:30 Greetings from Engineers of Philadelphia, C. E. Bonine (A'03) president, Engineers' Club of Philadelphia.

1:45 Plan and Purpose of Forums of American Engineering Council, F. A. Allner (A'12, M'14) vice-president, Pennsylvania Water and Power Company, Baltimore, Md.; chairman, AEC public affairs committee.

2:00 Labor Policy and Prospects for Employment, Leo Wolman, economist, National Bureau of Economic Research, professor of economics, Columbia University, New York, N. Y.

3:45 The Contributions of Technology to Employment, L. J. Fletcher, assistant general sales manager, Caterpillar Tractor Company, Peoria, Ill.; member, AEC executive committee.

Discussion.

Evening Session

Chairman—William McClellan (A'04, F'12) president, Potomac Electric Power Company; president AEC.

6:30 Dinner.

7:30 Technology and Competition, Stephen DuBrul, economist, General Motors Corporation, Detroit, Mich.

8:15 Relation of Technology to Finance, W. J. Kelly, president, Machinery and Allied Products Institute, and president, Arthur J. O'Leary and Sons, Chicago, Ill.

9:00 Summary of Conference.

Adjournment.

Objective of the AEC forums, as described by Mr. Allner, is to provide opportunities for the discussion with recognized authorities of various problems of public importance in which engineers should have a part.

Further details of the Philadelphia forum may be covered in later issues of Electrical Engineering.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. Electrical Engineering will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Wave Shape of Magnetizing Currents

To the Editor:

It has been known for a long time that the nonlinear relation between the flux and the magnetizing current in an iron-core transformer or choke coil results in the formation of harmonics in the magnetizing current. The magnitude of these harmonics can be obtained approximately by means of graphical methods. The following mathematical solution is, I believe, new.

Take the B-H curve for the iron and using the part of it between $B = 0$ and $B = B_M$—the latter point being flux density corresponding to E_{max} of the impressed electromotive force and express the relation in the form

$$H = K(B + aB^n + bB^{n_1} +) \tag{1}$$

Then if the impressed electromotive force is sinusoidal, $B = K_1 \sin x$ and

$$I = K_2H = KK_2\,[K_1 \sin x + a(K_1 \sin x)^n + b(K_1 \sin x)^{n_1} + \ldots] \tag{2}$$

In general two terms of equation 2 will be sufficient to provide a formula which fits the B-H curve fairly closely. $(\sin x)^n$ may be expanded in terms of odd harmonics as follows:

$$(\sin x)^n = \frac{\left[\sin x - \frac{n-1}{n+3}\sin 3x\right]}{D} + \frac{\left[\frac{(n-1)(n-3)}{(n-3)(n+5)}\sin 5x\right]}{D}$$

where $D =$

$$1 + \frac{n-1}{n+3} + \frac{(n-1)(n-3)}{(n+3)(n+5)} + \ldots$$

As this series converges rather slowly it may be more convenient to use the following summation of the series:

$$D = 2^n\left[\Gamma\left(\frac{n}{2} + \frac{3}{2}\right)\right]^2\left[(n+2)\right]^{-1}$$

This may be readily evaluated by reference to a table of gamma functions.

A rigorous proof of these formulas is too lengthy to be given here, but it may be mentioned that they are valid for all positive values of n.

Very truly yours,

John L. Clarke (A'17, M'30)

(Transmission Engineer, The Bell Telephone Company of Canada, Montreal, Que.)

Magnetic Force of a Solenoid

To the Editor:

The method generally employed for determining the axial and radial components of the magnetic force of a one-layer cylindrical solenoid makes use of the vector potential. While no inherent difficulties are connected with this, the calculations nevertheless are lengthy. The method here described is simpler, as it presupposes only Ampere's law. It is known that this law, which is usually given in the form

$$dH = \frac{ids \sin \psi}{r^2}$$

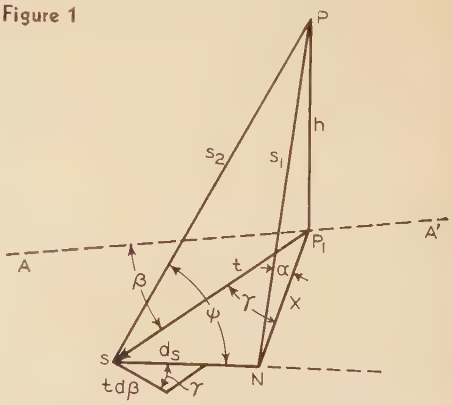
where i is the current, ds an element of the circuit, r the distance of the point for which dH is to be calculated from the element ds, and ψ the angle formed by ds and r. For a plane curve and for all points P in its plane this equation can be written

$$dH = \frac{id\beta}{r}$$

where β is the angle formed by r with a fixed straight through any point P. The question arises whether a similar transformation is also possible for points not in the plane of the curve. In figure 1 let h be the distance of point P from the plane of the curve of which ds is an element. Through the foot point P_1 of h the straight line AA' is drawn and the angle β is formed by the radius vector t and AA'. If s_2 is the distance from ds at point S to P then

$$dH = \frac{ids \sin \psi}{S_2{}^2} \tag{1}$$

Figure 1



where ψ is the angle formed by ds and s_2. This magnetic force is perpendicular to the plane formed by ds and S_2 and its axial component will be parallel to h. If we draw a perpendicular X from P_1 to the extension of ds and join its foot point N with P we obtain two rectangular triangles P_1NP and PNS. In these triangles

$$\frac{PN}{PS} = \frac{S_1}{S_2} = \sin\psi$$

and

$$\frac{P_1N}{PN} = \frac{X}{S_1} = \cos\alpha$$

In figure 2 these two triangles have each been rotated by 90 degrees in opposite directions through space around x and t as axis, respectively, and they both are now in the plane of the curve. The axial component dH_a is $dH \cos\alpha$, for dH is perpendicular to the plane of the triangle PSN and therefore also perpendicular to s_1. Furthermore

$$ds = \frac{t d\beta}{\cos\gamma} \text{ and } x = t\cos\gamma$$

Inserting all these values in equation 1 we obtain

$$dH_a = \frac{i ds \sin\psi \cos\alpha}{S_2^2} = \frac{it^2 d\beta}{s_2^3} = \frac{it^2 d\beta}{\sqrt{t^2+h^2}^3}$$

$$H_a = i\int_{\beta=0}^{2\pi} \frac{t^2 d\beta}{\sqrt{t^2+h^2}^3}$$

To calculate the axial component of the magnetic force of a cylindrical solenoid of any cross section with n turns, length l and with current I for any point P (figure 3) with a distance h_1 counted from the center plane of the solenoid we need only form the double integral

$$\frac{In}{\ } \int_{h=h_1-l/2}^{h_1+l/2} dh \int_{\beta=0}^{2\pi} \frac{t^2 d\beta}{\sqrt{t^2+h^2}^3} = H_{sa}$$

writing this

$$\frac{In}{l} \int_{h=h_1-l/2}^{h_1+l/2} \int_{\beta=0}^{2\pi} \frac{t^2 d\beta dh}{\sqrt{t\ +h^2}^3}$$

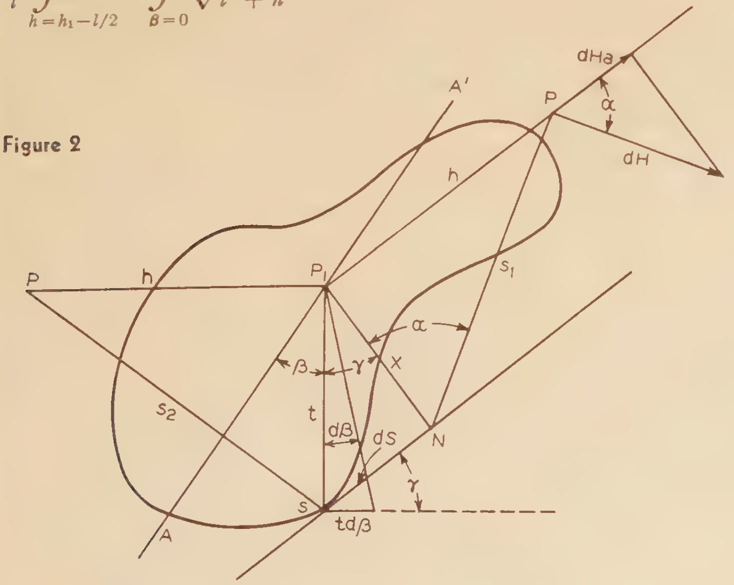


Figure 2

and performing the integration in regard to h, we obtain

$$\frac{In}{l}\int_{\beta=0}^{2\pi} d\beta \left.\frac{h}{\sqrt{t^2+h^2}}\right|_{h_1-l/2}^{h_1+l/2}$$

$$H_{sa} = \frac{In}{l}\int_{\beta=0}^{2\pi} d\beta \left[\frac{h_1+\frac{l}{2}}{\sqrt{t^2+\left(h_1+\frac{l}{2}\right)^2}} - \frac{h_1-\frac{l}{2}}{\sqrt{t^2+\left(h_1-\frac{l}{2}\right)^2}}\right]$$

If the cross section is a circle of radius R, then for the axis of the cylinder or solenoid

$$H_{sa} = \frac{2\pi In}{l}\left[\frac{h_1+\frac{l}{2}}{\sqrt{R^2+\left(h_1+\frac{l}{2}\right)^2}} - \frac{h_1-\frac{l}{2}}{\sqrt{R^2+\left(h_1-\frac{l}{2}\right)^2}}\right]$$

Figure 3

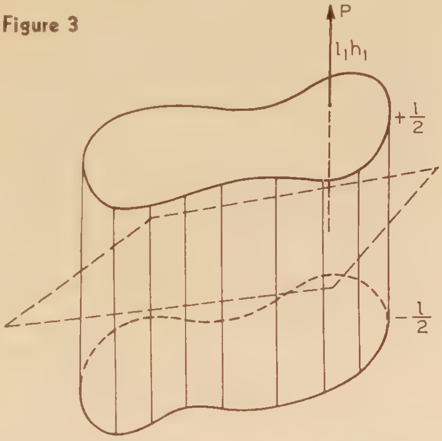
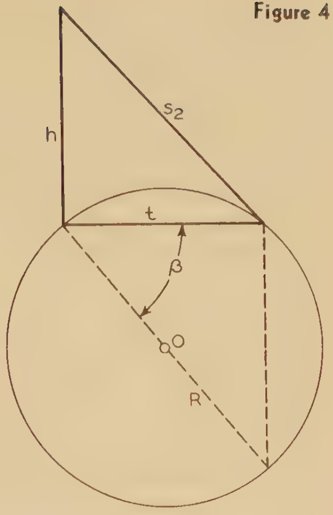


Figure 4



the well-known formula. If the point h_1 is situated in a perpendicular to the plane of the circles and passing through a point on its circumference then

$$H_{sa} = \frac{In}{l}\int_{\beta=0}^{2\pi} d\beta \left.\frac{h}{\sqrt{(2R)^2\cos^2\beta + h^2}}\right|_{h-l/2}^{h_1+l/2}$$

with regard to figure 4 we can write this, applying at the same time some transformations,

$$H_{sa} = \frac{2In}{l}\int_{\beta=0}^{\pi/2} \frac{h}{\sqrt{4R^2+h^2}} \times \left.\frac{d\beta}{\sqrt{1-\frac{h^2}{4R^2+h^2}\sin^2\beta}}\right|_{h_1-l/2}^{h_1+l/2}$$

For the center plane $h_1 = 0$ and

$$H_{sa} = \frac{2In}{\sqrt{4R^2+\left(\frac{l}{2}\right)^2}} \times \int_{\beta=0}^{\pi/2} \frac{d\beta}{\sqrt{1-\frac{4R^2\sin^2\beta}{4R^2+\left(\frac{l}{2}\right)^2}}}$$

But

$$\int_{\beta=0}^{\pi/2} \frac{d\beta}{\sqrt{1-\frac{4R^2\sin^2\beta}{4R^2+\left(\frac{l}{2}\right)^2}}}$$

is an elliptical integral which if R is assumed as $l/10 = 0.1l$, may be taken as $\pi/2$ and we therefore get

$$H_{sa} = \frac{In}{l}\,\frac{\pi}{\sqrt{0.04+0.25}}$$

while the axial component for the center is given by

$$\frac{2\pi In}{l\sqrt{0.01+0.25}}$$

which is about twice the value of that at the circumference.

To determine the axial magnetic force

for a solenoid with circular cross section for any point P we proceed in the following manner: In the integrals

$$\int_{\beta=0}^{2\pi} \frac{d\beta\left(h_1 + \frac{l}{2}\right)}{\sqrt{t^2 + \left(h_1 + \frac{l}{2}\right)^2}}$$

and

$$\int_{\beta=0}^{2\pi} \frac{d\beta\left(h_1 - \frac{l}{2}\right)}{\sqrt{t^2 + \left(h_1 - \frac{l}{2}\right)^2}}$$

in which $h_1 + l/2$ and $h_1 - l/2$ (figure 5) are perpendicular to t in space, therefore the factors multiplying $d\beta$ are sines of angles in rectangular triangles. Turning the triangle P_1PS with P_1S as axis by 90 degrees it then falls in the plane of the circle with radius R and O as center. As $h_1 + l/2$ and $h_1 - l/2$ are perpendicular to t their end points will describe circles with P' as center and with $h_1 + l/2$ and $h_1 - l/2$ as radii, respectively, when the extremity of t describes the circle with O as center.

From figure 5 it is readily seen that

$$\frac{h_1 + \frac{l}{2}}{s_2'} = \frac{VW}{2R} \text{ and } \frac{h_1 - \frac{l}{2}}{s_2''} = \frac{UW}{2R}$$

The lines $VW = z_1$ and $UW = z_2$ are obtained by joining the points of intersection of the lines s_2' and s_2'' and t with the circle of radius R. We therefore can write

$$\int_{\beta=0}^{2\pi} \frac{d\beta\left(h_1 \pm \frac{l}{2}\right)}{\sqrt{t_2 + \left(h_1 \pm \frac{l}{2}\right)^2}} =$$

$$\int_{\beta=0}^{2\pi} \frac{z_1 d}{2R}\beta - \int_{\beta=0}^{2\pi} \frac{z_2 d}{2R}\beta$$

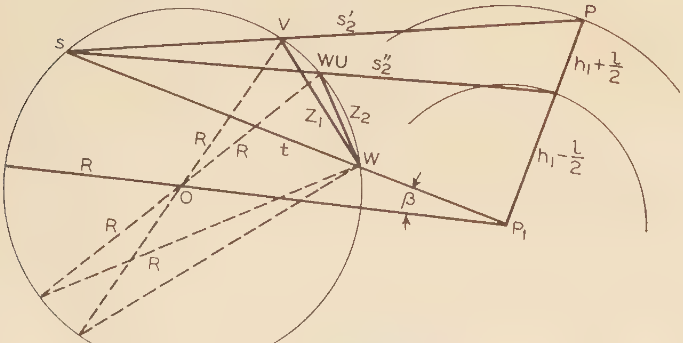


Figure 5

If we then plot the various values $\sqrt{z_1}$ and $\sqrt{z_2}$ on lines forming the respective angles β with OP_1 we obtain closed curves the areas of which expressed in polar co-ordinates will be porportional to the integrals

$$\int_{\beta=0}^{2\pi} \frac{d\beta\left(h_1 \pm \frac{l}{2}\right)}{\sqrt{t^2 + \left(h_1 \pm \frac{l}{2}\right)^2}}$$

as the area is given by

$$\int_{\beta=0}^{\beta_1} \frac{\sqrt{z^2 d\beta}}{2} = \frac{1}{2}\int_{\beta=0}^{\beta_1} z d\beta$$

To determine the factor of porportionality we proceed as follows: Let us assume that we have obtained the value of the area by aid of a planimeter with a constant c; that is, a reading b of the planimeter is equal to bc square centimeters. Therefore if

$$\int_{\beta=0}^{\beta_1} \sqrt{z^2 d\beta} = bc \text{ square centimeters}$$

then

$$\int_{\beta=0}^{\beta_1} z d\beta = 2bc$$

and bc/R is the value of the integral and finally

$$H_{sa} = \frac{In}{l}\frac{bc}{R} \times$$

If the point P_1 is situated within the circle then the curve the area of which represents

$$\int_{\beta=0}^{2\pi} \sqrt{z^2 d\beta}$$

surrounds this point, if P_1 is to the outside of the circle then these curves will be at one side of this point.

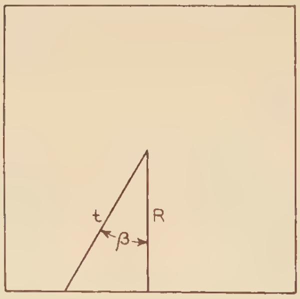


Figure 6

As I have pointed out the formula for H_{sa} holds good for a cylindrical solenoid of any cross section and we may easily apply it for figuring H_{sa} along the axis of a rectangular solenoid. If $2R$ be the length of the sides of the square then as shown in figure 6, $t = R/\cos\beta$ and

$$H_{sa} = \frac{8In}{l}\int_{\beta=0}^{\pi/4} \frac{hd\beta}{\sqrt{\left(\frac{R}{\cos\beta}\right)^2 + h^2}}\Bigg|_{h-l/2}^{h+l/2}$$

$$H_{sa} = \frac{8In}{l} \times$$

$$\int_{\beta=0}^{\pi/4} \frac{\left(h_1 \pm \frac{l}{2}\right)\cos\beta d\beta}{\sqrt{R^2 + \left(h_1 \pm \frac{l}{2}\right)^2 - \left(h_1 \pm \frac{l}{2}\right)^2 \sin^2\beta}}$$

and finally

$$H_{sa} = \frac{8In}{l}\left[\sin^{-1}\frac{1}{\sqrt{2}}\frac{h_1 + \frac{l}{2}}{\sqrt{R^2 + \left(h_1 + \frac{l}{2}\right)^2}} - \sin^{-1}\frac{1}{\sqrt{2}}\frac{h_1 - \frac{l}{2}}{\sqrt{R^2 + \left(h_1 - \frac{l}{2}\right)^2}}\right]$$

The similarity of this expression with that of a solenoid with circular cross section is evident, a result which one would expect. For small values of the arc this may be written

$$H_{sa} = \frac{8In}{\sqrt{2}l}\left[\frac{h_1 + \frac{l}{2}}{\sqrt{R^2 + \left(h_1 + \frac{l}{2}\right)^2}} - \frac{h_1 - \frac{l}{2}}{\sqrt{R^2 + \left(h_1 - \frac{l}{2}\right)^2}}\right]$$

It is not possible to develop a graphical method for the determination of the radial component of a solenoid with circular cross section with β as independent variable. But by introducing polar co-ordinates with the center of the circle as origin and with the angle ϕ at the center as independent variable we obtain an expression which readily can be integrated and permits also of a graphical solution. Starting again from equation 1 we obtain

$$dH_r = \frac{iRd\phi \sin\psi \sin\alpha}{S_2^2}$$

where (figure 1)

$$\sin\psi = \frac{S_1}{S_2}$$

$$\sin\alpha = \frac{h}{s_1}$$

and (figure 7)

$$S_2 = \sqrt{R^2 + \rho^2 - 2\rho R\cos\phi + h^2}$$

therefore

$$dH_r = \frac{ihRd\psi}{\sqrt{R^2 + \phi^2 - 2\phi R\cos\psi + h^2}^3}$$

While all differentials dH_{sa} of H_{sa} fall in the same direction, namely that of h, this is no longer true of the differentials dH_r, each of which falls in the direction of the respective radius R belonging to the element $Rd\psi$. But by inspection of figure 7 it is evident that dH_r may be decomposed into one component falling in the direction of ρ the line joining the foot point P_1 of h with O and into another perpendicular thereto. For reasons of symmetry these latter cancel out while the former being $dH_r \cos\phi$ add up to form a resultant in the direction OP_1 and we so obtain for the radial component of the solenoid

$$dH_r = \frac{In}{l} \int\limits_{h=h_1-l/2}^{h_1+l/2} dh \times$$

$$\int\limits_{\phi=0}^{2\pi} \frac{d\phi Rh \cos\phi}{\sqrt{R^2+\rho^2+h^2-2\rho R\cos\phi}^{\,3}}$$

The first integration gives

$$-\frac{In}{l} \times$$

$$\int\limits_{\phi=0}^{2\pi} \frac{R\cos\phi d\phi}{\sqrt{R^2+\rho^2+h^2-2\rho\, R\cos\phi}}\Bigg|_{h_1-l/2}^{h_1+l/2}$$

For reasons of symmetry this may be written

$$-\frac{2In}{l} \times$$

$$\int\limits_{\phi=0}^{\pi} \frac{R\cos\phi d\phi}{\sqrt{R^2+\rho^2+h^2-2\rho R\cos\phi}}\Bigg|_{h_1-l/2}^{h_1+l/2}$$

By making the following substitutions

$$\phi = (\pi - 2X)$$

$$d\phi = -2dX$$

$$\cos\phi = -\cos 2X$$

and

$$\cos 2X = 1 - 2\sin^2\frac{X}{2}$$

the integral is transformed to

$$-\frac{4InR}{l} \int\limits_{X=\pi/2}^{0} \frac{(1-2\sin^2 X)dX}{\sqrt{(R+\rho)^2+h^2}\sqrt{1-k^2\sin^2 X}}\Bigg|_{h_1-l/2}^{h_1+l/2}$$

where

$$k^2 = \frac{4R\rho}{(R+\rho)^2+h^2}$$

Bearing in mind that

$$\int\limits_{X=\pi/2}^{0} \frac{dX}{\sqrt{1-k^2\sin^2 X}} = -K$$

or the elliptical integral of first order and

$$\int\limits_{X=\pi/2}^{0} \frac{dX}{\sqrt{1-k^2\sin^2 XdX}} = -E$$

or the elliptical of second order (see appendix) and by reversing the order of substitution the final result is

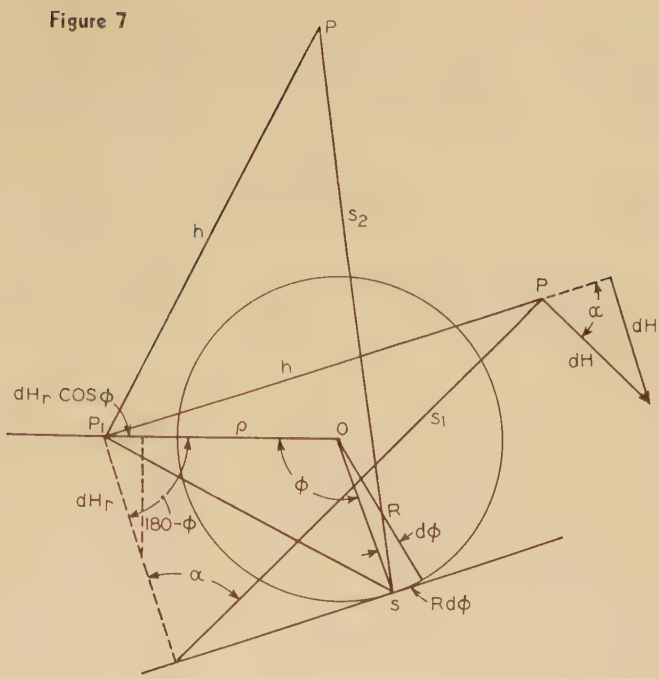


Figure 7

$$H_r = \frac{2In}{l}\sqrt{\frac{R}{\rho}}\left\{\frac{2}{k}(K-E_1)-kK\right\}\Bigg|_{h_1+l/2}^{h_1-l/2}$$

For the center plane of the solenoid h_1 is zero and therefore H_r is zero irrespective of ρ as the value of the expression in brackets for the upper and lower limit is numerically equal but with reversed sign. This signifies that the center plane is an equipotential surface and the lines of magnetic force are perpendicular to this plane. It is also easily seen that the end planes are no equipotential surfaces, while for the axis of the solenoid no radial component exists.

For the graphical solution we again start from the integral expression

$$H_r = -\frac{2In}{l} \times$$

$$\int\limits_{\phi=0}^{\pi} \frac{R\cos\phi\, d\,\phi}{\sqrt{R^2+\rho^2+h^2-2\rho R\cos\phi}}\Bigg|_{h_1-l/2}^{h_1+l/2}$$

By referring to figure 8 we see that

$$\sqrt{R^2+\rho^2+h^2-2\rho R\cos\phi}\Big|^{h_1+l/2}$$

is represented by the line $SP \equiv S_2$ in the rectangular triangle P_1SP. Constructing a second rectangular triangle having S_2 as hypotenuse and $R\cos\phi$ as second side forming with S_2 angle X_1 we then prolong $R\cos\phi$ until it intersects at U with the circle of radius R and O as center. Drawing a diameter $2R$ from the second point of intersection V of S_2 with the circle, then the rectangular triangle VWU will be similar to triangle PQS and therefore

$$\frac{R\cos\phi}{\sqrt{R^2+\rho^2+\left(h_1+\frac{l}{2}\right)^2-2\rho R\cos\phi}} =$$

$$\frac{VU}{VW} \equiv \frac{X_1}{2R}$$

In like manner for the distance $h_1-l/2X_2$ is obtained.

If we plot $\sqrt{X_1}$ and $-\sqrt{X_2}$ as radius vector under the respective angle ϕ from O as center, then again the area of the so formed curve will be proportional to the radial component of the magnetic force, and by multiplying with the same constants as above, namely

$\frac{In}{l}\,\frac{bc}{R}$ (b planimeter reading, c constant of planimeter) we finally get H_r.

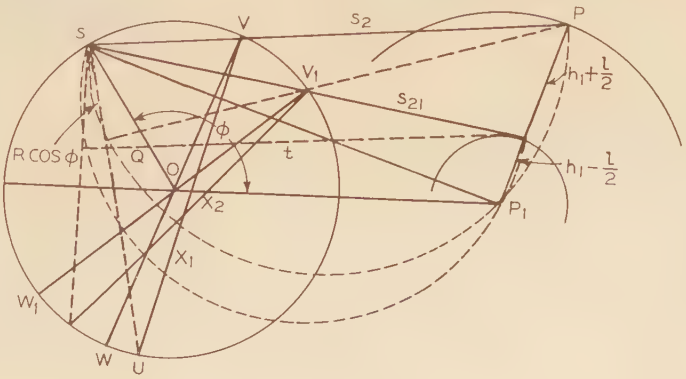


Figure 8

APPENDIX

Although the transformations of the integral

$$S = -\int_{X=\pi/2}^{0} \frac{(1 - 2\sin^2 X)dX}{\sqrt{R^2 + \rho^2 + h^2 + 2\rho R(1 - 2\sin^2 X)}}$$

to obtain the elliptical integrals are quite elementary we shall carry them out here in more detail than in the text. We will write

$$S = -\int_{X=\pi/2}^{0} \frac{(1 - 2\sin^2 X)\,dX}{\sqrt{(R+\rho)^2 + h^2} \times \sqrt{1 - \frac{4R\rho\sin^2 X}{(R+\rho)^2 + h^2}}}$$

and writing for

$$\frac{4R}{(R+\rho)^2 + h^2} = k^2$$

the expression

$$S = -\frac{1}{\sqrt{(R+\rho)^2 + h^2}} \times \left\{\int_{X=\pi/2}^{0} \frac{dX}{\sqrt{1 - k^2\sin^2 X}} - \int_{X=\pi/2}^{0} \frac{2}{k^2} \frac{k_2 \sin^2 X\,dx}{\sqrt{1 - k^2\sin^2 X}}\right\}$$

$$\int_{X=\pi/2}^{0} \frac{dX}{\sqrt{1 - k^2\sin^2 X}} = -K$$

or the elliptical integral of the first order with reversed sign

$$\int_{X=\pi/2}^{0} \frac{2}{k^2} \frac{k^2\sin^2 X dX}{\sqrt{1 - k^2\sin^2 X}} =$$

$$\int_{X=\pi/2}^{0} \frac{2}{k^2} \frac{[1 + k^2\sin^2 X - 1]dx}{\sqrt{1 - k^2 \sin^2 X}} = M$$

$$-M = -\int_{X=\pi/2}^{0} \frac{2}{k^2} \sqrt{1 - k^2\sin^2 X}dX + \int_{X=\pi/2}^{0} \frac{2}{k^2} \frac{dX}{\sqrt{1 - k^2\sin^2 X}}$$

and

$$\int_{X=\pi/2}^{0} \sqrt{1 - k^2\sin^2 X}dX = -E$$

or the elliptical integral of second order with reversed sign.

Very truly yours,
LIONEL FLEISCHMANN
(Aloey Ferguson Company, Cincinnati, Ohio)

Personal Items

W. R. WHITNEY (A'01) recently received the Marcellus Hartley Gold Medal of the National Academy of Sciences "to mark the appreciation of the National Academy of Sciences for eminent services to the public, performed without a view to monetary gains and by methods which in the opinion of the Academy are truly scientific." Doctor Whitney was born at Jamestown, N. Y., August 22, 1868. He was graduated from the Massachusetts Institute of Technology with the degree of bachelor of science in 1890, and in 1896 received the degree of doctor of philosophy from Leipzig University. Honorary degrees since have been conferred upon him by several universities. Since his graduation from Massachusetts Institute of Technology, Doctor Whitney has held the following positions at that institution: assistant instructor in general chemistry (1890–92), sanitary chemistry (1896–98), instructor in theoretical chemistry and proximate analysis (1898–1901), assistant professor of theoretical chemistry (1901–04), nonresident associate professor of theoretical chemistry (1904–08), and nonresident professor of chemical research since 1908. In 1900, when the research laboratories of the General Electric Company were established at Schenectady, N. Y., Doctor Whitney was appointed director of research. In 1928 he became vice-president of the company and director of research. In 1932 he retired from active service and was made vice-president in general charge of research, which position he has since held. Although Doctor Whitney's greatest personal activity has been in the field of chemistry, he has directed many researches that have made outstanding contributions to the electrical industry. He has contributed generously to technical literature, having published more than 80 papers. Doctor Whitney received the AIEE Edison Medal in 1934, and among the many other honors he has received are the Willard Gibbs Medal, 1916; Chandler Medal, 1920; Perkin Medal, 1921; the Gold Medal of the National Institute of Social Sciences, 1928; and the Franklin Medal, 1931. Doctor Whitney is a member of many technical societies and is a member for life of the Institute.

W. R. WHITNEY

E. F. PEARSON (A'20, F'37) has relinquished his duties as chief engineer of the Northwestern Electric Company, Portland, Ore., to become assistant to the president of the Pacific Power and Light Company, Portland. In his new position his services will be available in an advisory capacity to the Northwestern Electric Company. Mr. Pearson was born October 26, 1890, at Virginia City, Nev., and was graduated from the University of Nevada in 1912 with the degrees of bachelor of science and electrical engineer. He joined the Northwestern Electric Company immediately following his graduation, and has served that company continuously, except for a brief service in the United States Army during the World War. He became chief engineer in 1935. Mr. Pearson was chairman of the AIEE Portland Section during 1923–24, and during the same year he was a member of the national membership committee. At present he is a member of the committee on power generation, and is general chairman of the 1938 Pacific Coast convention.

E. F. PEARSON

J. P. JACKSON (A'92, F'12) for many years in charge of personnel for the Consolidated Edison Company of New York, Inc., New York, N. Y., and the United Electric Light and Power Companies, recently retired from active service. Colonel Jackson was born September 27, 1868 in Philadelphia, Pa., and was graduated from Pennsylvania State College with the degrees of bachelor of science in mechanical engineering (1887) and mechanical engineer (1892). Later the University of Pittsburgh conferred upon him the degree of doctor of science. His first position in the electrical industry was as a wireman for the Philadelphia Electric Company in 1889. Later he was associated with the Sprague Electric Company as superintendent of street railway construction before entering the teaching profession as director of the mechanical department of Fisk University in 1890. In 1892 Colonel Jackson was appointed to the faculty of Pennsylvania State College, where he remained until

1913, first as professor of electrical engineering and later as dean of the college of engineering. During the World War he was commissioned as a colonel in the United States Corps of Engineers, and for distinguished service was decorated by the French and Italian governments; he received a citation from the United States government for meritorious service. He joined The New York Edison Company as assistant to the vice-president in 1924 and two years later was made also manager of the personnel bureau. He became head of the personnel department of the Consolidated Edison Company in 1937. Colonel Jackson is author or co-author of several technical books and papers. He served the Institute as a member of the committees on education, 1926–28; and safety, 1926–30 (chairman 1926–28). He has served as Institute representative on the Commission of Washington Awards, National Fire Protection Association, National Fire Waste Council, National Safety Council, and the advisory committee to the Museum of Science and Industry of New York (chairman 1926–37). He is a member for life of the Institute and a member of The American Society of Mechanical Engineers, Franklin Institute, Eta Kappa Nu, and other scientific and social organizations.

William Arthur (A'12, M'17) has been appointed Philadelphia (Pa.) district office manager of the Allis-Chalmers Manufacturing Company. Mr. Arthur was born in England in 1880 and received his technical education at the Lancashire Railway Technical Institute and at Liverpool University. After serving an engineering apprenticeship at Horwich, England, he became assistant engineer in the electric traction divison of the Lancashire and Liverpool Railway, later being appointed assistant resident electrical engineer in charge of the Liverpool-Southport electrified systems. In 1907 he came to the United States and was employed in the electric railway department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Later Mr. Arthur became engaged in various manufacturing and consulting engineering activities before becoming affiliated with the American Brown-Boveri Electric Corporation in 1925. When that company's electrical interests were absorbed by the Allis-Chalmers Company in 1931, Mr. Arthur was retained as special representative for railway traction and mercury arc rectifiers, with offices at New York, N. Y. Mr. Arthur is a member of the American Transit Association.

G. A. Anderegg (A'04, M'30) has retired as cable development engineer of the Bell Telephone Laboratories, New York, N. Y. Mr. Anderegg was born at Ragersville, Ohio, March 30, 1873, and was graduated from Oberlin College with the degree of bachelor of science in 1899. He then attended Harvard University, where he received the degrees of bachelor of arts and master of arts in 1900 and 1902, respectively. Following his graduation in 1902 he joined the Western Electric Company at Chicago, Ill., and a year later was transferred to the development laboratory in New York. In 1904 he returned to Harvard University to fill a temporary appointment as instructor in electrical engineering. During the three following years he served as associate professor of electrical engineering at The Ohio State University, but returned to the engineering department of the Western Electric Company in New York in 1908. Since 1909 Mr. Anderegg has been engaged in the development and design of lead covered telephone cables, and since 1913 has been in charge of that work, first for the Western Electric Company, and later for the Bell Telephone Laboratories.

W. K. Dunlap (A'89, F'12) has retired as acting vice-president of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Mr. Dunlap was born December 5, 1869 at Rochester, N. Y., and received his formal technical education at the University of Rochester. He began his industrial career with the Westinghouse Company as an apprentice engineer following his graduation in 1892. Two years later he was sent to Niagara Falls, N. Y. He remained there for six years as resident manager of operation, then went to Europe to observe electrical progress in Italy and Switzerland. Upon his return to the United States he became superintendent of construction for the Westinghouse Company. In 1904 Mr. Dunlap was promoted to the position of managing director of Westinghouse interests at the Louisiana Purchase Exposition at St. Louis, Mo. During the following year he became assistant to the vice-president and for several years directed service operations of the company. Mr. Dunlap is a member for life of the Institute.

R. A. McCarty (A'16, M'32) recently was transferred to South Philadelphia, Pa., as manager of the steam and stoker division of the Westinghouse Electric and Manufacturing Company. Formerly Mr. McCarty was manager of the small motor division of that company, with offices at Lima, Ohio. A native (1882) of Mooresburg, Tenn., he was graduated from the University of Tennessee in 1903, following which he entered the test course of the Westinghouse Company. He entered the power engineering division in 1906, and three years later was assigned to motor engineering. In 1910 he was made engineer in charge of insulation design and became section engineer a year later in the power engineering department. In 1928 Mr. McCarty was appointed division engineer, and two years later became manager of the power engineering department. He became manager of the generator division in 1935, and was transferred to Lima as manager of the small motor division in 1938.

W. L. Cisler (M'35) recently became assistant chief engineer, electric engineering department, Public Service Electric and Gas Company, Newark, N. J. Mr. Cisler was born October 8, 1897, at Marietta, Ohio, and was graduated from Cornell University with the degree of mechanical engineer in 1922. Immediately following his graduation he became associated with the Public Service Electric and Gas Company as a cadet engineer, and has been associated with that organization continuously. In 1926 he became assistant chief engineer at the Paterson (N. J.) generating station, in the following year he was made chief engineer at the Marion generating station, and in 1931 he was made planning and installation engineer in the Newark offices. Mr. Cisler became general superintendent of generation in 1935, and one year later was appointed assistant general manager.

C. E. Stryker (A'21, F'35) has become a partner of the consulting-engineering firm of McKinsey, Wellington, and Company, Chicago, Ill. Mr. Stryker is a native (1897) of Chicago, and received the degrees of bachelor of science in electrical engineering (1917) and electrical engineer (1924) at the Armour Institute of Technology. For two years following his graduation he was employed as testing engineer for the Commonwealth Edison Company, Chicago. In 1920 Mr. Stryker became assistant professor of electrical engineering at Armour Institute of Technology, and at the same time served as electrical engineer for the Ozone Pure Airifier Company; later he served in the same capacity for the Underwriters Laboratories. In 1923 he became affiliated with the Fansteel Products Company, eventually becoming chief engineer and remaining with that company until 1936, when he resigned to join McKinsey, Wellington, and Company. He is a member of the Society of Automotive Engineers.

L. A. Pipes (A'37) has been appointed instructor in electrical engineering in the graduate school of engineering at Harvard University, Cambridge, Mass. A native (1910) of Mexico City, Mexico, Doctor Pipes was graduated from California Institute of Technology with the degree of bachelor of science in 1933. In the following year he enrolled as a graduate student at that institution, receiving at the same time an appointment as assistant in electrical engineering. At the end of that scholastic year he received his master of science degree, and in 1936 was granted the degree of doctor of philosophy. During 1936–37 Doctor Pipes was an instructor in electrical engineering at The Rice Institute, Houston, Texas, and in 1937–38 he was alumni research fellow at the University of Wisconsin, Madison. Doctor Pipes' new appointment becomes effective September 1, 1938.

A. V. Karpov (M'22) recently resigned his position as designing engineer for the Aluminum Company of America, Pittsburgh, Pa., to devote his entire time to private practice as a consulting engineer, with offices in Pittsburgh. Mr. Karpov is a native (1886) of Kursk, Russia, and was graduated from the Darmstadt (Germany) Technical College and the Kharkov (Russia) Technical Institute. After serving as engineer in charge of several engineering projects in Russia and Germany, he came to the United States in 1920 and secured employment as an engineer and designer for the Standard Arch Company, New York, N. Y. He has been associated with the Aluminum Company of America since 1928. In 1936 Mr. Karpov was awarded the Thomas Fitch Rowland prize of the American Society of Civil Engineers as co-author of a paper relating to bridge design.

H. F. Boe (M'30) has been made manager of the service department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Mr. Boe is a native (1884) of Mansfield, Ohio, and attended Carnegie Institute of Technology. He became affiliated with the Westinghouse Company in 1903 as a dynamo and motor tester, and continued at the East Pittsburgh works until 1915. For one year, during 1916–17 Mr. Boe was chief engineer and manager of the Vaile Kimes Company, Dayton, Ohio, following which he returned to the Westinghouse Company as a sales engineer in the Rochester, N. Y. offices. Since 1922 he has been successively manager of the Buffalo (N. Y.) sales office; eastern district sales manager, with headquarters in New York, N. Y.; and commercial manager.

H. A. McLaughlin (A'24, M'30) has been appointed test engineer in charge of the electric testing section of Central Hudson Gas and Electric Corporation, Poughkeepsie, N. Y. Mr. McLaughlin became associated with that company as relay engineer in 1929 and has been protection engineer for several years. He was graduated in electrical engineering from the Polytechnic Institute of Brooklyn in 1923, following which he was engaged in test work and the design and application of protective equipment for the Brooklyn Edison Company. He was associated briefly with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., before joining the Central Hudson Gas and Electric Corporation.

E. J. Watz (A'28, M'34) recently was appointed branch manager of the General Electric X-Ray Corporation, Minneapolis, Minn. Mr. Watz was born in 1901 at Stockholm, Sweden, and has been affiliated with the General Electric X-Ray Corporation continuously since 1922. In that year he became a service engineer in the New York, N. Y. offices of that company; in 1925 he was made manager of the New York service department; and for the last ten years he has been engaged in sales engineering work.

C. R. Beardsley (A'08, F'30) has been transferred to the Consolidated Edison Company of New York, Inc., New York, N. Y., as assistant manager of the contract control and inspection department. Mr. Beardsley formerly was general superintendent of distribution construction for the Brooklyn Edison Company, Inc., Brooklyn, N. Y. He is a director of the Institute.

N. C. Goin (M'24) has been made sales manager, gearing division, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa. Mr. Goin has been associated with the Westinghouse Company continuously since 1917, except for a two-year period in the United States Army during the World War. Since 1921 he has been a sales engineer in the Pittsburgh offices.

Ernest Thompson (A'33) sales representative for the Electric Controller and Manufacturing Company has been transferred to the St. Louis (Mo.) offices of that company. Mr. Thompson has been associated with the Electric Controller and Manufacturing Company since 1929 and has been assigned to the Chicago offices since 1935.

V. A. Hanson (A'34) vice-president and chief engineer of the Power Transmission Council, has been transferred from Boston, Mass. to Detroit, Mich., where he will conduct a transmission survey of manufacturing plants allied or identified with the automotive industry. Mr. Hanson has been located at the Boston headquarters for the last two years.

R. N. Stoddard (M'34) has been transferred to the Westinghouse Electric and Manufacturing Company lamp division, Bloomfield, N. J. In his new position Mr. Stoddard will specialize in problems in electronics. Formerly he was employed in the East Pittsburgh, Pa. works of the Westinghouse Company.

W. H. Harries (A'36) recently was appointed junior electrical engineer for the National Advisory Committee for Aeronautics at Langley Field, Va. Formerly Mr. Harries was a levelman for the United States Bureau of Reclamation, Coulee Dam, Wash.

J. R. Maull (A'37) recently became a cadet engineer for the Public Service Electric and Gas Company, Newark, N. J. Mr. Maull has been an assistant in the department of electrical engineering of Massachusetts Institute of Technology, Cambridge.

H. A. Egeberg (A'28) has been appointed investigating electrical engineer to the State Electricity Commission, Brisbane, Queensland, Australia. Formerly Mr. Egeberg was assistant electrical engineer for the department of public works, Brisbane.

J. N. Keck (A'37) recently became a student engineer for the Illinois-Iowa Power Company, Champaign, Ill. Mr. Keck formerly was assistant to the chief of test department, Moloney Electric Company, St. Louis, Mo.

F. E. Bell (A'35) has assumed new duties at Guntersville Dam, Ala. Mr. Bell has been assistant construction engineer for the Tennessee Valley Authority at the Joe Wheeler Dam, Ala. He is vice-chairman of the AIEE Muscle Shoals Section.

W. E. Peterson (A'36) has been transferred to the Manistee, Mich., offices of the Consumers Power Company as power and lighting sales engineer. Until recently Mr. Peterson has been a draftsman in the Saginaw (Mich.) offices of that company.

W. F. Bergmann (A'36) has become assistant chief electrical designer for the engineering firm of Holway and Neuffer, Tulsa, Okla. Mr. Bergmann formerly was associated with the Public Utility Engineering and Service Corporation, Chicago, Ill.

Obituary

Malcolm Vau Watson (A'07, M'32) vice-president and general manager of the West Coast Power Company, California Public Service Company, and Western States Utilities Company, Portland, Ore., died April 25, 1938. Mr. Watson was born at Marquette, Kans., October 16, 1874, and was graduated from Kansas University in 1898 with the degree of bachelor of science in electrical engineering. After holding several preliminary positions he became chief electrician for the United States Reduction and Refining Company in 1902, remaining there until 1906, when he went to Zamora, Mexico, to become superintendent of hydroelectric stations for the Guanajuato Power Company. In the following year Mr. Watson was employed by the Colorado Power Company, Denver, as a designer of substations. In 1909 he became general manager of the Arizona Power Company, and six years later assumed the additional duties of chief engineer. Mr. Watson had been vice-president and general manager of the West Coast Power Company and its associated companies since 1927.

John William Freidenmann (M'30) district representative for the General Electric Company, Dubuque, Ia., died February 13, 1938. Mr. Friedenmann was born at Bennington, Vt., July 23, 1896, and attended Union College. In 1916 he was employed by the General Electric Company, Schenectady, N. Y., as a draftsman. In 1918 he became an engineer for the American Brake Shoe and Foundry Company, Erie, Pa., but remained there for only one year before joining the sales and advertising department of the Electric Service Supply Company. In 1923 he established his own electrical contracting and engineering business at Bennington, Vt., continuing in that business until 1928 when he became a regional merchandise specialist for the General Electric Company.

Anatoli Constantinovitch Seletzky (A'29, M'35) associate professor of electrical engineering, Case School of Applied Science, Cleveland, Ohio, died May 11, 1938 after a brief illness. Born May 29, 1905, at Volynia, Russia, Doctor Seletzky came to the United States and studied at The Johns Hopkins University, where he received the degree of bachelor of science in electrical engineering in 1927. After serving briefly with the Brooklyn Edison Company and the Westinghouse Electric and Manufacturing Company, he returned to Johns Hopkins to study, and received the doctor of engineering degree there in 1930. In the same year he was appointed instructor in electrical engineering at Case School of Applied Science; in 1933 he was appointed assistant professor, and in 1937 was promoted to the rank of associate professor. Doctor Seletzky wrote many technical papers on electric circuit theory, power transmission lines, transformers, and amplifiers, and frequently was called as an expert consultant in patent litigations involving those subjects. He was a member of the current AIEE committee on instruments and measurements. In 1936 he received honorable mention in the selection of America's outstanding young electrical engineer by Eta Kappa Nu. He was a member of Tau Beta Pi and Sigma Xi.

Maynard Dodd (M'24) assistant vice-president of the Commercial Cable Company, New York, N. Y., died April 10, 1938. Mr. Dodd was born April 1, 1869 at Glasgow, Scotland, and attended the West of Scotland Technical College. In 1886 he became an operator for the British Government Telegraphs, and remained with that service until 1889, when he resigned to join the Anglo-American Telegraph Company. Mr. Dodd became chief electrician of the Commercial Pacific Cable Company in 1905, with headquarters at Honolulu, T. H. In 1921 he was transferred to that company's head office at New York, N. Y., as an executive engineer, and one year later was appointed assistant vice-president of the Commercial Cable Company.

Henry Augustus Ratcliff (M'22) chief electrical engineer, London Power Company, Ltd., London, England died April 26, 1938. Mr. Ratcliff was born in 1877 at Nottingham, England, and received his technical education at the University College, Nottingham. In 1897 he became a member of the staff of the Manchester Corporation Electricity Department, where he held various positions, eventually becoming superintendent electrical engineer in 1921. Concurrently he served for many years as demonstrator and lecturer in the Manchester College of Technology. He became chief electrical engineer of the London Power Company in 1928.

Henry William Clothier (M'17) director of A. Reyrolle and Company, Ltd., Hebburn-on-Tyne, England, died March 11, 1938. Mr. Clothier was born in London, England, April 3, 1872, and was educated at St. Mark's College Schools and the City and Guilds of London Institute. For ten years he was employed by S. Z. DeFerranti, Ltd., London, holding various positions including the managership of the switchgear department. Mr. Clothier was associated with A. Reyrolle and Company for more than 34 years.

Timothy A. J. Hayes (A'32) director of the Boston Police Signal Service, Boston, Mass., died April 14, 1938. Mr. Hayes was born in Boston, January 11, 1882 and attended Franklin Union (Boston). From 1901 until 1911 he was associated with the Holtzer-Cabot Electric Company, Brookline, Mass. In the latter year he resigned to become director of the Boston Police Signal Service, a position he held for 26 years.

Membership

Recommended For Transfer

The board of examiners, at its meeting on May 12, 1938, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Clem, J. E., electrical engineer in central station department, General Electric Company, Schenectady, N. Y.
Terry, C. A., general superintendent, electrical department, New York Power and Light Company, Albany, N. Y.
Wood, H. B., chief electrical engineer, Stone and Webster Engineering Corporation, Boston, Mass.

3 to Grade of Fellow

To Grade of Member

Keller, C. W., sales engineer, General Electric Company, Denver, Colo.
Kidd, G. B., research engineer, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.
Lawson, F. I., engineer, Federal Power Commission, Chicago, Ill.
Lorje, Herman, statistical engineer, State Highway Department of Colorado, Denver.
Low, H. M., refinery engineer, Phillips Petroleum Company, Bartlesville, Okla.
Mason, G. U., general electrical foreman, Guntersville Dam, Ala.
Mauseau, C. M., consulting engineer, Brooklyn, N. Y.
Page, G. I., operating engineer, Southwestern Light and Power Company, Lawton, Okla.
Park, J. G., mains engineer, North Metropolitan Electric Power Supply Company, London, England.
Sanderson, D. G. P., general electrical supterintendent, Donnacona Paper Company, Ltd., Donnacona, P. Q., Canada.
Singer, F. J., telegraph switching engineer, Bell Telephone Laboratories, Inc., New York, N. Y.
Sirotkin, G. A., draftsman, Cutler-Hammer, Inc., Milwaukee, Wis.
Smith, Frank, equipment engineer, The Teleregister Corporation, New York, N. Y.
Torrance, A. E., manager, Wolstenholme (Pty), Ltd., Johannesburg, South Africa.

14 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1938, or August 31, 1938, if the applicant resides outside of the United States or Canada.

United States and Canada

Albrighton, R. F., General Railway Signal Company, Rochester, N. Y.
Anthony, W. T., Ohio Bell Telephone Company, Cleveland, Ohio.
Armistead, R. B., 402 Cameron Street, Chattanooga, Tenn.
Asper, I. F., Atlantic Refining Company, Philadelphia, Pa.
Austin, F. M., Houston Lighting and Power Company, Houston, Tecas.
Ball, M. B., Southern California Edison Company, Ltd., Bell, Calif.
Barth, A. H., Square D Company, Houston, Texas.
Beamish, R. J. Jr., Rural Electrification Administration, Washington, D. C.
Berry, T. M., General Electric Company, Schenectady, N. Y.
Blume, A. E., 22 Maple Street, Brooklyn, N. Y.
Bork, M. J. Jr., Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.
Bound, P. T., Canadian Westinghouse Company, Ltd., Hamilton, Ontario.
Brown, H. I., Freeport Sulphur Company, Port Sulphur, La.
Buchman, R. P., Ohio Bell Telephone Company, Cleveland.
Bunyan, R. P. (Member), Ohio Bell Telephone Company, Cleveland.
Caress, A. E., Loup River Public Power District, Columbus, Nebr.
Casper, C. H., Carter Oil Company, Seminole, Okla.
Cogbill, B. A., General Electric Company, Pittsfield, Mass.
Connolly, W. T., Empire Mill Company, Spokane, Wash.
Currie, G. J., Ohio Bell Telephone Company, Cleveland.
Curry, G. W., General Electric Company, Houston, Texas.
Cuthbertson, L. J., City Clerk's Office, Girard, Kansas.
D'Agostino, V. F., Western Electric Company, Kearny, N. J.
Dign, G. N., Atlantic City Electric Company, Atlantic City, N. J.
Donahue, J. J., Allis-Chalmers Manufacturing Company, Kansas City, Mo.
Doran, F. M., Donnacona Paper Company, Ltd., Donnacona, Que., Canada.
Dyer, H. R., Bethelehem Steel Corporation, Sparrows Point, Md.
Elberfeld, J., Rochester Athenaeum and Mechanics Institute, Rochester, N. Y.
Elliott, A. R., Houston Lighting and Power Company, Galveston, Texas.
Ffolliott, C. F. (Member), Associated Electric Laboratories, Inc., Chicago, Ill.
Fontaine, C. B., Jr., General Electric Company, Lynn, Mass.
Foss, E. (Member), Pacific Telephone and Telegraph Company, San Francisco, Calif.
Frederick, E. H., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Gallo, J. E., 116 Grove Street, Brooklyn, N. Y.
Gawley, B. P., YMCA, Schenectady, N. Y.
Gmeiner, E. V. (Member), Citizens Light and Power Company, Adrian, Mich.
Godsey, H. H., Tishomingo County Electric Power Association, Iuka, Miss.
Gray, J. L. (Member), Citizens Light and Power Company, Adrian, Mich.
Greear, H. B., General Electric Company, Atlanta, Ga.
Guckel, H. B., New York and Queens Electric Light and Power Company, Long Island City, N. Y.
Harper, J. A., General Electric Company, Schenectady, N. Y.
Hord, D. A., Northwestern Electric Company, Portland, Ore.
Hunt, O. D., Kansas State College, Manhattan.
Ingerson, W. E., Bell Telephone Laboratories, Inc., New York, N. Y.
Inman, D. E., Westinghouse Electric and Manufacturing Company, Cleveland, Ohio.
James, R. T., Radio Station WOR, New York, N. Y.
Jamison, J. S., Jr., Virginia Military Institute, Lexington.
Jones, D. H., Bulldog Electric Products Company, New York, N. Y.
Kallenbach, G. K., New York Power and Light Corporation, Albany, N. Y.
Karr, C. L., Western Electric Company, Inc., Kearny, N. J.
Krughoff, I. F., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Leahey, E. W., Ohio Brass Company, Philadelphia, Pa.
Lee, W. M., Kelley-Koett Manufacturing Company, Covington, Ky.
Loye, P. E. (Member), Reda Pump Company, Bartlesville, Okla.
Lundell, R. H., Puget Sound Navy Yard, Bremerton, Wash.
McDonald, F. J., E. I. Du Pont de Nemours, Wilmington, Del.
Meyer, G. A., Southwestern Bell Telephone Company, Dallas, Texas.
Miller, F. J. (Member), Buffalo Niagara Electric Corporation, Niagara Falls, N. Y.
Musket, P. P., H. G. Fischer and Company, Chicago, Ill.
Myles, A. H., Electric Controller and Manufacturing Company, Cleveland, Ohio.
Nickerson, L. T., Westinghouse X-Ray Company, New York, N. Y.
Partridge, H. R., Le Carbone Company, Inc., Boonton, N. J.
Pratt, J. L., 1515 Sante Fe Building, Dallas, Texas.
Raabe, V., The Carlisle and Finch Company, Cincinnati, Ohio.
Ray, G. W., Yankee Network, Inc., Bridgeport, Conn.
Reid, L. R., Allis-Chalmers Manufacturing Company, New York, N. Y.
Robinson, H. B. (Member), Carolina Power and Light Company, Raleigh, N. C.
Roche, W. A., National Bureau of Standards, Washington, D. C.
Sandin, J. (Member), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Scheldorf, M. W., General Electric Company, Schenectady, N. Y.

Spiak, A., Interborough Rapid Transit System, New York, N. Y.
Stacy, J. D. (Member), General Electric Company, Pittsfield, Mass.
Tambling, R. L., Bell Telephone Laboratories, Inc., New York, N. Y.
Taylor, R. H., Narragansett Electric Company, Providence, R. I.
Temple, G. H., Jr., Massachusetts Institute of Technology, Cambridge.
Tesche, C. F., 816 Summit Street, Linden, N. J.
Tierney, P. V., Reda Pump Company, Bartlesville, Okla.
Troup, D. J., 512 Cafawissa Avenue, Sunbury, Pa.
Von Soreny, E., 511 East 78 Street, New York, N. Y.
Waddington, C. V. (Member), Kansas Gas and Electric Company, Wichita, Kans.
Whelpley, E. K., Bureau of Engineering, San Francisco, Calif.
Wolff, R. S., Connecticut Light and Power Company, Waterbury, Conn.
Wright, W. D., Indiana Bell Telephone Company, Indianapolis, Ind.
Zambell, H. G., 1009 Weschler Avenue, Erie, Pa.

Total, United States and Canada—84.

Elsewhere

Atkins, J. W. (Member), Octavius Steel and Company, Ltd., Calcutta, India.
Franks, H. B. S., Hull Corporation Electricity Department, Ferensway, Hull, England.
Horn, J. G., A Reyrolle and Company, Ltd., Hebburn-on-Tyne, England.
Hunter, A., British Thomson-Houston Company, Ltd., Rugby, Warwicks, England.
Oldham, C. A. (Member), Weston Electrical Instrument Company, Ltd., Enfield, Middlesex, England.
Patell, R. J. R. (Fellow), Parsi Technical and Industrial Institute, Majura Gate, Surat, India.

Total, elsewhere—6.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

(A) MANUAL of PHYSICAL MEASUREMENTS. By A. Zeleny and H. A. Erikson. Sixth edition. New York and London, McGraw-Hill Book Company, 1937. 237 pages, diagrams, charts, tables, 8 by 6 inches, cloth, $2.25. An outline of laboratory experiments for university courses in general physics.

DIFFERENTIAL and INTEGRAL CALCULUS. 2 volumes. By R. Courant, translated by E. J. McShane. Revised edition. New York, Nordemann Publishing Company, 1937. Diagrams charts, tables 9 by 6 inches, cloth volume 1, 616 pages, $5.00; volume 2, 682 pages, $7.00. The first volume corresponds to a beginning course. Volume II completes the study of functions of several variables and multiple integrals, continues differential equations, and takes up the calculus of variations and complex variables.

ATM (Archiv für Technisches Messen), Lieferungen 75–77, September–November 1937. Munich and Berlin, R. Oldenbourg. Illustrations, 12 by 8 inches, paper, 1.50 rm. each. Three numbers of a monthly publication containing classified articles covering various types of apparatus and methods for technical measurements.

ADVANCED CALCULUS. By W. B. Fite. New York, Macmillan Company, 1938. 399 pages, diagrams., tables, 9 by 6 inches, cloth, $5.00. Assuming familiarity with the basic operations of calculus, discusses functions of more than one variable, indefinite, infinite, and multiple integrals, various types of series, and applications to geometry.

VDE VORSCHRIFTEN. Berlin, Verband Deutscher Elektrotechniker, 1937. Diagrams, tables, charts, 9 by 6 inches, paper, apply. Supplements to the book of standards issued by the Society of German Electrical Engineers, giving new or revised regulations. The subjects covered are high-voltage a-c apparatus, electric heating apparatus, heavy-current overhead lines, antennas, the testing of insulators, and electric railroads.

MATHEMATICS for ELECTRICAL STUDENTS. By H. M. Keal and C. J. Leonard. Second edition. New York and London, John Wiley & Sons, 1938. 225 pages, illustrations, 7 by 5 inches, cloth, $1.60. Intended for industrial workers, trade school and technical high school students.

(The) LOW VOLTAGE CATHODE-RAY TUBE. By G. Parr. London, Chapman & Hall, 1937. 177 pages, illustrations, 9 by 5 inches, cloth, 10s. 6d. (obtainable from Allan B. Du Mont Laboratories, 542 Valley Road, Upper Montclair, New Jersey). Intended to give an insight into the cathode-ray tube and its technique to those who use it in work in some branches of science. The construction and operation of the tube, focusing and performance, Lissajous' figures and time bases are discussed. Various applications of the tube to radio engineering and other industries, television and photography are described.

LIGHT, Principles and Experiments. By G. S. Monk. New York and London, McGraw-Hill Book Company, 1937. 477 pages, illustrations, 9 by 6 inches, cloth, $5.00. Textbook and laboratory manual for the advanced study of geometrical optics, classical physical optics, and the more recent extensions of physical optics dealing with the origin of spectra, the interaction of light and material media, and the effects on that interaction of external electric and magnetic fields.

LIGHT, PHOTOMETRY and ILLUMINATING ENGINEERING. By W. E. Barrows. Second edition. New York and London, McGraw-Hill Book Company, 1938. 445 pages, illustrations, 9 by 6 inches, cloth, $4.00. Contains revised chapters on light sources, illumination calculations, and interior and street lighting and new chapters on gas and vapor lamps, lighting for recreations and sports, and the lighting of highways and airways.

(The) J. & P. TRANSFORMER BOOK. By S. A. Stigant and H. M. Lacey. Seventh edition. London, Johnson & Phillips, Ltd., 1937. 916 pages, illustrations, 9 by 6 inches, cloth, 6s. 6d. Deals with principles, specifications, connections, windings, tests, grounding, protection, and transformer oil, with diagrammatic and mathematical explanations.

INDUSTRIELLE ELEKTROWÄRME, Edited by Wirtschaftsgruppe Elektrizitätsversorgung. Teil 3: WO WIRD ELEKTROWÄRME MIT VORTEIL ANGEWENDET. Berlin, Arbitsgemeinschaft zűr Förderung der Elektrowirtschaft, 1937. 116 pages, illustrations, 8 by 6 inches, paper, 1 rm. Tables of the electric heating processes and equipment which may be used advantageously in various industries.

HANDBOOK of CHEMISTRY and PHYSICS. Edited by C. D. Hodgman. Twenty-second edition. Cleveland, Chemical Rubber publishing Company, 1937. 2,069 pages, tables, 7 by 5 inches, cloth, $6.00; students' edition, $3.50. This reference work has undergone the customary annual revision. About 50 pages have been added, and revisions and corrections made throughout the book, to bring the information up to date or present it more conveniently.

Great Britain. Department of Scientific and Industrial Research. ILLUMINATION RESEARCH Technical Paper No. 20. The USE of COLORED LIGHT for MOTOR CAR HEADLIGHTS. London, His Majesty's Stationery Office, 1937. 32 pages, tables, 10 by 6 inches, paper (obtainable from British Library of Information, 270 Madison Ave., New York, $0.30). A report on the relative desirability of white and colored headlights on motor cars.

ENGINEERING LAW. By R. E. Laidlaw and C. R. Young. Toronto, University of Toronto Press, 1937. 380 pages, tables, 9 by 6 inches, cloth, $4.00. A presentation of those phases of law that impinge in some manner on the acts, duties and liabilities of the engineer. Not intended as a legal text, but presents facts concerning contracts, specifications, industrial disputes, patents, company organization, and questions in connection with boundaries, surveys, and other technical matters. The references are to Canadian and English law reports.

ELETROWÄRMETAGUNG BERLIN, 5 June 1936 in Marmorsaal des Zoologischen Gartens, veranstaltet von der Wirtschaftsgruppe Elektrizitätsversorgung und Wirtschaftsgruppe Elektroindustrie. Berlin, Arbeitsgemeinschaft zür Förderung der Elektrowirtschaft, 1937. 100 pages, illustrations, 12 by 8 inches, paper, apply. A collection of papers presented at a joint meeting of the Wirtschaftsgruppe Elektrizitätsversorgung and the Wirtschaftsgruppe Elektroindustrie, on electric furnaces.

EISENLOSE DROSSELSPULEN. By J. Hak. Leipzig, K. F. Koehler, 1938. 316 pages, illustrated, 10 by 7 inches, cloth, 28 rm. A large part of this treatise on air-core reactors is devoted to the mathematical analysis of the induction effects in various types.

ELECTRICAL MEASUREMENTS. By F. A. Laws. Second edition. New York and London, McGraw-Hill Book Company, 1938. 739 pages, illustrated, 9 by 6 inches, cloth, $6.00. Designed to be a "compendium of methods" for the practical man as well as a textbook for electrical engineering students. Covers basic measurements of current, resistance, potential difference, electromotive force, inductance, capacitance, and power, and describes industrial meters, instrument transformers, calibration, determination of wave form, and cable testing.

ÉLECTRICITE et MAGNÉTISME. By G. Jochmans and F. Descans. Brussels, A. De Boeck; Paris, Librairie Polytechnique Ch. Béranger, 416 pages, diagrams, tables, cloth, 150 Belgian francs. A textbook for mechanical- and electrical-engineering students. Section I, on general theory, covers fields, forces and applications in electrostatics, magnetostatics, and electromagnetism, as well as electric currents and induction phenomena in general. Section II treats the application of electrical theories to electrical apparatus.

HOCHSPANNUNGSTECHNIK. By A. Roth. Second edition, edited by A. Imhof. Vienna, Julius Springer, 1938. 624 pages, illustrated, 9 by 6 inches, cloth, 39 rm. This discussion of high-voltage technique begins with the properties of electric fields and a description of materials of high dielectric strength used in high-voltage work. The properties of insulating oils and air in an electric field are considered, as well as of oil and air in connection with solid materials.

HOW to FILE BUSINESS PAPERS and RECORDS. By A. Chaffee. New York and London, McGraw-Hill Book Company, 1938. 166 pages, illustrated, 8 by 6 inches, cloth, $2.00. Discusses in detail filing systems and their operation, filing routines and filing equipment, showing the advantages of certain types which make them particularly valuable in various specific cases.

HOW to KEEP ACCOUNTS and PREPARE STATEMENTS. By E. A. Saliers. New York, Ronald Press Company, 1938. 481 pages, charts, tables, 8 by 5 inches, cloth, $3.00. Intended for those who wish a practical understanding of accounting, but lack time or opportunity for a formal course of instruction.

INDEX to ASTM STANDARDS and TENTATIVE STANDARDS as of January 1, 1938. Philadelphia, Pa., American Society for Testing Materials, 1938. 119 pages, 9 by 6 inches, paper, gratis. Contains both a classified index and a numerical list of all standards as of January 1, 1938; these standards cover specifications, test methods, and definitions as adopted by the Society.

PRINCIPLES of RADIO. By K. Henney. Third edition, New York, John Wiley & Sons, 1938. 495 pages, illustrated, 8 by 5 inches, cloth, $3.50. In this edition, as in the earlier ones, the intent is to provide a book useful for independent study as well as for classroom use.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Transactions

Papers and Discussions Comprising Pages 1–60 of the 1938 Volume

Electrical Studies of Living Tissue—II

Correlation Between Tissue Response and Voltage Distribution

By A. G. CONRAD
ASSOCIATE AIEE

H. W. HAGGARD
Mem. Am. Physiol. Soc.

B. R. TEARE
MEMBER AIEE

ALTHOUGH opinion differs as to whether tissue response to electrical stimulation results directly from imposed electrical quantities or indirectly from accompanying chemical changes, there is general agreement that the response occurs when a definite threshold value of some changing condition within the tissue has been reached. Bishop[1] supports the belief that response results when a definite polarization is developed within the tissue; Hill[2] associates response with a threshold value of cathode potential. We present here evidence to show that response occurs when a definite internal voltage has been built up in the tissue. Our conclusions are based on data obtained from oscillograms of this internal voltage.

In 1907 LaPique[3] established the relations between the intensity and duration of currents producing minimal responses in tissue; he described the process of excitation as analogous to the charging of a leaky condenser. Since then numerous investigators[6–9] have demonstrated that tissue possesses capacitance. Hill[2] and Blair[4] have shown that an equivalent circuit with properly proportioned constants could be used to explain the intensity duration curve obtained by LaPique.[3] In a previous paper[5] we have demonstrated the effects of tissue capacitance on the shape of the voltage waves across tissue during the passage of current impulses of rectangular wave shape.

Using the voltage wave shapes as criteria of circuit constants, this work has been extended here to define the character of the equivalent circuits. We find that for rectangular waves of current 0.001 to 0.0001 second in duration and from 1 to 10 times the rheobase (the rheobase current is the minimum current that will produce a response, that is, it is the current represented by the ordinate of the horizontal asymtote to the intensity-duration curve) value in intensity that human and frog tissue behaves electrically as a simple circuit consisting of one condenser and one or more resistors. The magnitude of tissue impedance remains constant throughout the duration of the impulse.

The correlation between tissue response and the voltage distribution in the tissue has been determined and is here described on the basis of the voltage distribution in the equivalent circuits.

General Method

In determining the electrical characteristics of tissue, a current of rectangular wave shape was applied and the accompanying voltage wave across the tissue was recorded. The numerical values of the components of the impedance thus indicated were calculated. They were confirmed by the passing of the current impulse through a suitable circuit—and equivalent circuit—containing the necessary resistances and capacitances to give a duplication of the voltage wave.

To obtain current impulses of rectangular wave shape suitable for the electrical analysis of tissue a special apparatus was developed. This apparatus and its particular advantages have been described by the authors.[5]

Electrical Characteristics of Human Tissue

We have previously[5] described the characteristics of human tissue that have led us to correlate the tissue responses with the voltage distribution in equivalent circuits. These characteristics are: (1) minimal response occurs in human tissue when the potential across the tissue reaches a certain threshold value; (2) the voltage required to produce a minimal response in different human beings may be different, but for a given individual it is a constant, regardless of the duration of the impulse; (3) the current required to produce a minimal response is a function of the duration of the impulse. The time intensity relations obtained by the authors are similar to those obtained by other investigators.

Our point of departure from previous investigations of

A paper recommended for publication by the AIEE committee on instruments and measurements. Manuscript submitted August 16, 1937; released for publication October 25, 1937.

A. G. CONRAD and B. R. TEARE are assistant professors of electrical engineering and H. W. HAGGARD is associate professor of applied physiology at Yale University, New Haven, Conn.

[1] For all numbered references see list at end of paper.

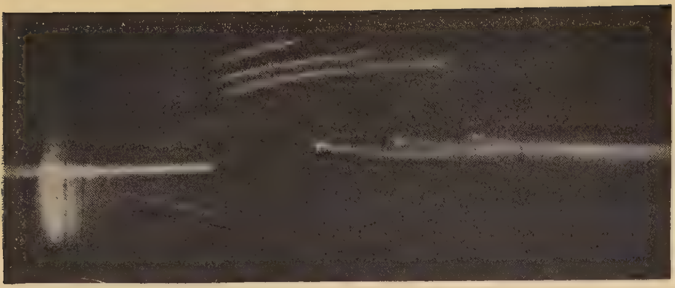


Figure 1. Minimal response voltage waves for shocks of different durations

this kind was in recording the voltage wave across the tissue at the time of stimulation. Although the currents required to produce responses are a function of duration of the impulses, the accompanying voltages are constant for each subject.

Electrical Characteristics of Frog Tissue

The methods by which the measurements were made on the frog have been described by the authors.[5] The voltage wave of frog tissue is of distinctly different shape from that obtained across human tissue, indicating a different type of equivalent circuit. The dissymmetry between the voltage produced across frog tissue and that produced across a resistor, although only slight, indicates that the frog's tissue is not purely resistive. The circuit that most nearly expresses the electrical equivalent of frog's tissue is shown in figure 3; that of human tissue in figure 7.

Figure 1 shows 3 superimposed voltage waves produced by current impulses of different duration causing minimal responses. In contrast to the result obtained in human tissue, the peak voltages at minimal response in the frog are not constant. The relations of peak voltages to currents at minimal response for different durations have been shown.[5]

The differences between the shapes of the curves showing the relation of peak voltages to duration in human and frog tissue can be explained on the basis of the difference in the nature of the equivalent circuits of tissue. It is evident from the waves shown in figure 1 that the voltage does not drop to zero at the instant that the current is stopped. Furthermore this residual voltage appears to be constant regardless of the intensity and duration of the impulse producing minimal responses. In order to determine more accurately the magnitude of this residual voltage the sensitivity of the amplifier supplying the cathode ray oscillograph was increased so that the upper part of the voltage wave was moved off the oscillograph screen and the residual voltage appeared approximately 2 centimeters high. A series of minimal-response shocks was then administered and the corresponding residual voltages photographed. Figure 2 shows 3 such voltages for shocks of different durations. This residual voltage, when referred to the equivalent circuit, figure 3, is that which appears across the parallel part at the instant the current is shut off.

Our interpretation of these findings is that minimal response of frog tissue occurs when, and only when, the voltage across the parallel portion has been built up to a definite value.

Correlation of Equivalent Circuits to Living Tissue

An explanation of the shapes of the curves for the time intensity relations at minimal response and also the corresponding curves for peak voltages of different tissues is afforded here on the basis of the voltage produced in the equivalent circuit by the passage of current.

In the case of frog's tissue let figure 3 represent the equivalent circuit; R_1 and R_2 the number of ohms in the series and parallel portions of this circuit; C the capacity in farads; i_1 the instantaneous current in C; i_2 the instantaneous current in R_2; I the current supplied to the circuit; T its duration. A current of rectangular wave shape supplied to this circuit will produce a voltage wave corresponding to that of figure 1 and shown here in a diagram as figure 4. The distance *ab* (figure 4) represents the voltage across R_1 produced by the current I. When the current is shut off the voltage across R_1 disappears giving a reduction in voltage of *cd*. For a rectangular current wave the rise in voltage (*ab*) is equal to the drop in voltage *cd*. When the current is first applied the condenser acts as a short circuit on the resistor R_2; consequently the voltage E_2 is zero and at this instant E_1 is equal to the total circuit voltage E. After the current has flowed for some time t a voltage builds up across the condenser. The magnitude of this voltage is determined by the current I, the resistance R_2, the capacity C, and the duration of the current impulse. The voltage E_2 can be expressed by the equation

$$E_2 = IR_2(1 - e^{-\frac{t}{R_2C}}) \qquad (1)$$

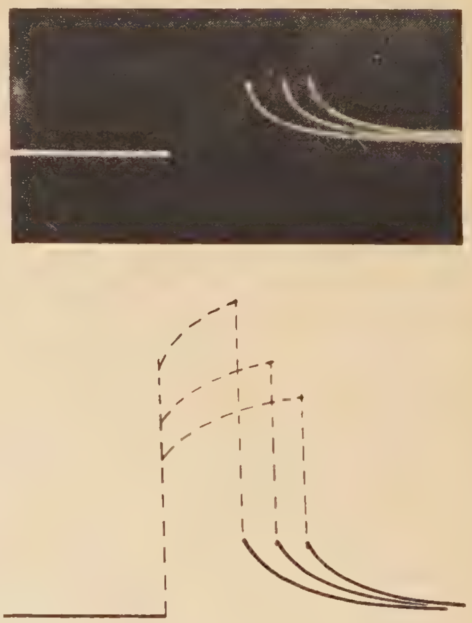


Figure 2. Threshold voltages in frog tissue produced by minimal response shocks

The total voltage across the circuit produced by a rectangular current wave is:

$$E = E_1 + E_2 = IR_1 + IR_2(1 - e^{-\frac{t}{R_2C}}) \quad (2)$$

The first term of this equation (IR_1) is represented by the distance *ab*, figure 4; the second term $IR_2(1-e^{-\frac{t}{R_2C}})$ is represented by the vertical distance between a horizontal line drawn through *b* and the curve *bc*. Since the distance *ab* is equal to *cd*, the distance *de* is equal to E_2 at the instant the current impulse is shut off.

It has been shown experimentally that E_2 at the instant the current is shut off is constant for impulses producing minimal response. Therefore for such impulses

$$E_2 = K = IR_2(I - e^{-\frac{T}{R_2C}}) \quad (3)$$

$$I = \frac{K}{R_2(1 - e^{-\frac{T}{R_2C}})} \quad (4)$$

Equation 4 is that for the minimal-response current curve. When T is infinite the term

$$e^{-\frac{T}{R_2C}}$$

becomes zero and I is equal to K/R_2, this particular value of I being the rheobase. As the duration of the applied current is decreased T becomes shorter and the value of I must necessarily increase to fulfill the requirements of equation 4.

The voltage across frog's tissue for an impulse of a rectangular current wave can be expressed as

$$E = IR_1 + IR_2(1 - e^{-\frac{t}{R_2C}}) \quad (5)$$

but the second term, which becomes

$$IR_2(1 - e^{-\frac{T}{R_2C}})$$

at the end of any minimal-response impulse is always constant regardless of the duration T. A minimal-response impulse of short duration therefore, requires a large value of I to keep this term constant and the total peak voltage E must consequently be higher for short impulses because of the increase in IR_1.

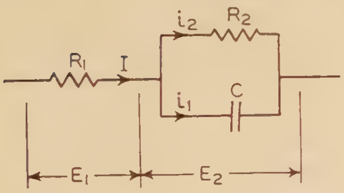


Figure 3 (left). Voltages in the equivalent circuit of frog tissue

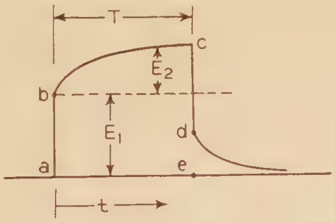
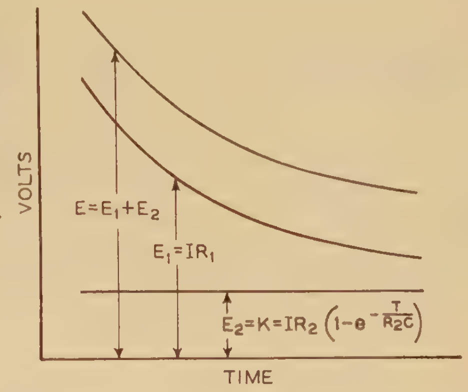


Figure 4 (right). Voltage wave for frog tissue

If the peak value of $E_2 = K$ (value at the end of the impulse) for impulses of various duration are plotted against duration as in figure 5, it will be represented as a horizontal line. The first term of equation 5 (IR_1) must take the form as plotted on the same axes. The total voltage across the tissue producing the minimal response will be the sum of these 2 terms which gives a curve corresponding to the total voltage E.

Since the voltage across the parallel part of the circuit attains a definite peak value at the instant any minimal response impulse is shut off, it is evident that the peak current i_2 which flows through R_2 (figure 3) must build up to a definite peak value for each impulse causing minimal response. If this final peak value of i_2 is plotted against the duration of the impulse, it will be constant as shown in figure 6. If the impulse duration is exceedingly long so that the condenser current is zero, this peak value of current i_2 will be equal to the total current I which in this case is equal to the rheobase K/R_2.

Figure 5. Peak voltages for shocks of different durations (minimal response)



From equation 4 it has been shown that the current required to produce a minimal response is

$$I = \frac{K}{R_2(1 - e^{-\frac{T}{R_2C}})}$$

(when K is the threshold voltage of the parallel circuit) and that the rheobase current, $I_{Rh} = K/R_2$. Since $I = i_1 + i_2$ and, at the instant prior to "shut off" of the current, the peak value of $i_2 = K/R_2$, then the current i_1 which flows through the condenser at this instant is

$$i_1 = I - i_2$$

$$= \frac{K}{R_2(1 - e^{-\frac{T}{R_2C}})} - \frac{K}{R_2}$$

When T is infinite the first and second terms of this equation are equal and i_1 is zero. For impulses of shorter duration the value of i_1 prior to shutting off I, will be

$$i_1 = \frac{K}{R_2(e^{\frac{T}{R_2C}} - 1)}$$

From these facts it follows that if the duration were exceedingly short the current i_1 would necessarily be infinite. The final value of i_1 for each shock of minimal response when plotted against duration is shown in figure 6. The sum of the currents i_1 and i_2 are also shown. The resultant curve expresses the time intensity relation for minimal response.

On representing the equivalent circuit of human tissue by the diagram and notations of figure 7, equation 1 (previously applied to figure 3) will represent the voltage produced across the circuit (or tissue) by a rectangular current wave. We have shown experimentally that this peak voltage is constant for any impulse producing minimal response. The current necessary to produce minimal response is therefore expressed by equation 4. The curves shown in figure 1 can be derived from equation 2. The equation which expresses the voltage necessary to produce a minimal response in frog tissue with a rectangular current wave, is also applicable to human tissue. In this particular case R_1 is zero and

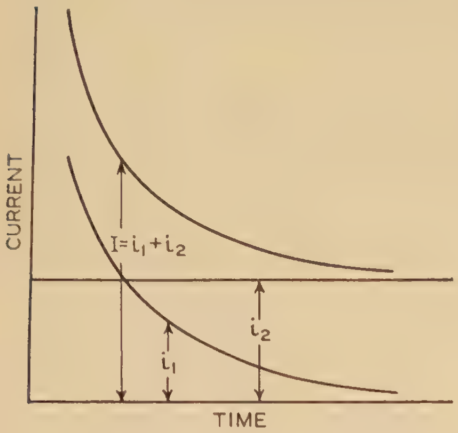


Figure 6. Peak current at instant of shut-off for minimal response shocks

$$E = IR_2\left(1 - e^{-\frac{T}{R_2C}}\right) = K$$

Therefore the differences in the minimal-response voltage curves of frog and human tissue can be attributed to and explained by the differences existing in the equivalent circuits representing these tissues.

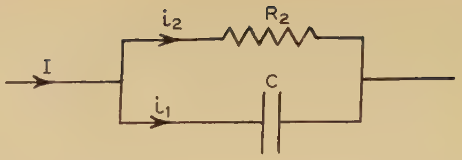


Figure 7. The equivalent circuit of human tissue

It must be remembered that an equivalent circuit of living tissue is not physiological in nature. It is used in the same manner as the equivalent circuits of other conductors of electricity, such as transformers or motors. It is used here only as a means of explaining the correlation between some of the electrical and physiological characteristics of living tissue. Other equivalent circuits could be used for this purpose. These other circuits since they are equivalent circuits naturally reveal the same correlations.

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A New High-Speed Distance-Type Carrier-Pilot Relay System

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Synopsis: This paper outlines the reasons for application of pilot relay equipment, particularly of the carrier-current type. A one-cycle carrier-pilot-relay scheme is described which now makes available the desirable high-speed and back-up characteristics of step-type distance protection combined with the 100 per cent simultaneous tripping feature possible with a pilot circuit. Impedance and over current supervised single-phase directional elements are utilized for controlling carrier on phase and ground faults, respectively.

Introduction

THE ADVANTAGES and necessity of rapid fault clearing have been long recognized. Improved engineering means have been gradually made available for accomplishing this object so that starting with circuit breaker operating times of a half second and relay times ranging up to several seconds 10 years ago, developments have made available up to the present day standard 8-cycle breakers and relays operating in one cycle, on a 60-cycle basis. In some instances breaker times as low as 3 cycles have been obtained.

The chart in figure 1 illustrates the gain in clearing time of transmission line faults available with increased speeds of relays and circuit breakers. Clearing times from 30 to 120 cycles are common with the 24-cycle breakers and induction-type relays using time as a basis for selectivity. A major improvement is generally available in systems of any complexity by going to high-speed relays and again by improving the breaker speed to 8 cycles. The further gain available by the addition of carrier pilot is of particular importance when the maximum clearing time for a fault anywhere in line section is the determining factor in major features of system design.

A number of such situations listed herewith are indicative of factors now leading to the application of carrier pilot protection on numerous systems.

1. *Stability.* Simultaneous clearing improves system stability and increases the loads which may be safely carried over parallel interconnecting lines.

2. *Quick Reclosing.* Simultaneous tripping is essential to fast reclosing, the combination being particularly effective in increasing stability with single tie lines.

3. *Shock to System.* System shock, evidenced by voltage dips and dropping of synchronous load is lessened by fast clearing.

4. *System Design Flexibility.* Desirable system arrangements are made possible by carrier relaying which could not be relayed with sufficient speeds to permit their use otherwise.

5. *Growth of Faults.* The more serious 3-phase and double ground faults generally originate as line-to-line or single ground and with sufficient speed of clearing the spreading to other phases is greatly reduced.

6. *Ground Relaying Improved.* On systems where high-speed ground relaying is not feasible otherwise, carrier pilot provides an ideal solution.

7. *Out-of-Synchronism.* The carrier channel provides means for preventing operation of protective relays due to power swings or out-of-synchronism conditions while still clearing faults during such conditions.

8. *Simultaneous Faults.* The added basis for discrimination makes possible superior relay performance under the condition of simultaneously occurring faults.

9. *Joint Use.* From an economic point of view joint use of the carrier channel for point to point communication, or for control or remote metering may indicate the use of carrier pilot where thr relaying requirements alone would not justify it.

Step-type distance-relay protection is the use of 2 or preferably 3 impedance or distance measuring elements set for successively greater distances and successively longer times. The action of this principle relay protection is readily shown for a simple series connection of line sections with sources only at the ends. While practical systems are seldom so simple, the flexibility of setting provided by this arrangement in obtaining both high-speed and back-up protection has proved its adaptability to a large proportion of the systems in this country and Canada. Approximately 2,000 relays operating on this principle are in use. The importance of this point must be stressed since the provision of adequate and selective back-up protection is frequently a more difficult relay application problem than the high-speed protection.

Figure 2 illustrates the "step" characteristic tripping time versus fault location graph of a 3-zone impedance relay on a single series system. The breaker time must be added to the time here indicated to get the clearing time as shown in figure 1. The tripping characteristic of figure 2 is obtained by the use of relay elements responsive separately to 3 quantities, namely:

1. Distance of fault from the breaker.
2. Direction of fault from the breaker.
3. Time from the beginning of fault.

Three of the distance elements are required, one directional element and one timing element having 2 separately adjustable time contacts to obtain the characteristic of figure 2. The contacts on these elements are arranged in the trip circuit as shown in figure 3. Considering breaker number 1, faults to the left do not close the directional contact D. In the first zone, the directional contact D is closed together with all 3 distance elements $Z1$, $Z2$, and $Z3$. The breaker is tripped through D and $Z1$ without awaiting the closure of the timer contacts, $T2$ or $T3$. Thus, for the first zone the tripping time is simply the operating time of the high-speed directional and distance elements, normally under one cycle. The second

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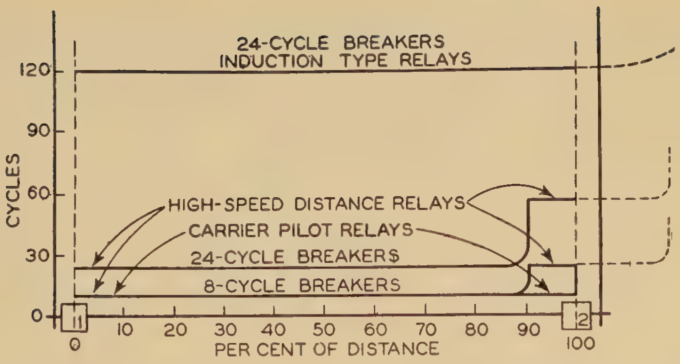

Figure 1. Reduction of clearing times by modernization

and third elements would also trip after a time delay, for faults in this region, but this is of no consequence since the first element has tripped the breaker.

The second zone is beyond the distance setting of the first zone element and $Z1$ therefore remains open for faults in this region, the tripping taking place through contacts D, $Z2$, and $T2$. The prime function of the second zone is to trip breaker number 1 for faults between zone 1 and breaker number 2. This distance is quite short, about 10 per cent of the section length, but cannot be entirely eliminated due to the practical accuracies of distance relays, current and potential transformers and application data. However, the second zone element also has a very important function in opening the breaker number 1 with suitable time delay in case of faults occurring to the right of breaker 2 on bus or lines, which are not properly cleared due to the failure or absence of apparatus to perform this function. Such failure may be in breakers, trip coils, or relays, or there may be small unprotected sections on which the expected frequency of fault occurrence does not warrant relay protection.

The third zone extends through the end of the next adjacent section so that breaker number 1 backs up breaker 3 for faults anywhere in the section 3–4. The second and third zones provide selectivity between the back-up protection of adjacent sections without the necessity of greater time settings in successive sections since the third zone for one section selects with the second zone for the next section.

The addition of carrier pilot to the scheme extends the zone of high-speed tripping up to breaker number 2, as shown dotted in figure 2 and eliminates the tripping time indicated by the shaded area. This is accomplished by a contact on the carrier receiving or blocking relay labeled RR in figure 3. This relay is controlled by the fault detectors and carrier current so that its contacts only close if the fault is within the protected section. The trip circuit is completed through D, $D2$, and RR, and also slightly faster through D and $Z1$ except for faults in the remote end zone.

The addition of carrier current pilot with separate relays for its control would involve a bulky and expensive addition to the relay equipment. It is a major purpose of this paper to show that the requirements for carrier control overlap the requirements of the distance relay elements and have made possible the combination of carrier

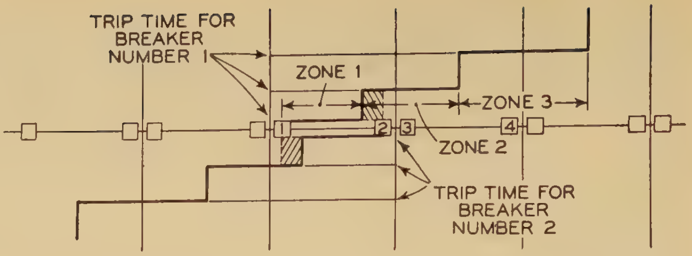
TRIP TIME FOR BREAKER NUMBER 1
ZONE 1
ZONE 3
ZONE 2
1
2
3
4
TRIP TIME FOR BREAKER NUMBER 2

Figure 2. Chart of step-type distance relays

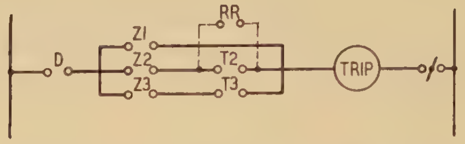

Figure 3. Elementary diagram of distance-relay carrier-current scheme

pilot action with the step-type distance protection with very little added relay equipment.

Most of the variations in manner of utilizing the carrier pilot channel, which were considered in the earlier stages of development have been discarded in favor of the scheme which may be termed rather generally, "Intermittent With Normally Blocked Trip Circuit." The carrier is used in a straight telegraph manner, that is, unmodulated, and the principal implications of the name are:

1. That the carrier is transmitted, at least for the relaying function only at times of fault or test.

2. That advantage is taken of the inherently faster operating possibility of fault detector relays, which need not integrate effect over time, as compared with directional elements which must integrate forces over a definite time to obtain a correct operating indication. Because of this inherent difference carrier may be started and the normally blocked trip circuit may always be transferred by the fault detectors to control by carrier while the directional elements are making up their minds which way the power flows.

After the carrier is started by the fault detectors, the control of carrier and hence tripping is on a directional basis. If both directional indications point in, carrier transmission is stopped at both ends, the receiver relay closes its contacts RR and tripping is permitted.

With this general picture in mind, the requirements of the carrier controlling elements may be stated.

1. Fault detectors for starting carrier should be separate from those for tripping under carrier control, and should be set for a lower operating value, for both phase and ground faults. This is to insure that the carrier starting element at one end of the line always functions when the tripping element at the other end of the line operates. The third zone and second zone distance elements have the necessary relationship for carrier starting and tripping fault detectors, and substantially equivalent action must be provided for ground faults.

2. A directional element is required which will close a contact as rapidly as possible when and only when the fault power through the breaker is flowing into the line. Closure of this contact is necessary only if the fault lies somewhere within the protected sections. The second zone trip circuits of a high-speed distance relay possess this characteristic since at least one of them (for the faulty phase) will close through D and $Z2$ whenever the fault is within the pro-

tected section and none will close for faults back of the breaker. Also, none will close due to load conditions on the unfaulted phases since the distance elements will not be operated by loads.

Thus, the third zone element $Z3$ may be used for carrier starting and the second zone trip circuit D and $Z2$ may be used as the directional combination for controlling carrier after it is started by the fault detectors. Since these elements are available in the high-speed distance relay, they are used together with the corresponding ground elements as illustrated in the wiring diagram figure 4 and schematic diagram figure 5, showing the arrangement of a highly successful operating scheme built on the principles just outlined.

The upper part of schematic diagram figure 5 comprises the tripping circuits and the lower part of the carrier control circuits. The conventional distance type trip paths are: First zone D and $Z1$; second zone D, $Z2$, and $T2$; third zone D, $Z3$, and $T3$. The carrier-controlled tripping path is composed of D, $Z2$, and *RRP* contacts. For ground protection a carrier controlled trip circuit can be set up through the contacts D_0 and I_{02} of the ground relay and the carrier controlled contact *RRG*. The contacts *RRP* and *RRG* are on the blocking relay controlled by the carrier signal.

The contacts $Z3$ (A, B, and C) in the lower part of figure 5 serve to start the transmission of the carrier signal for phase faults and the contact I_{03} performs the same function for ground faults. These carrier start contacts $Z3$ are on the same fault detector elements as the tripping contacts $Z3$ in the upper part of the diagram. The ground carrier start contact I_{03} is operated by an overcurrent element separate from that which operates the tripping contact.

Normally, with phase and ground carrier start contacts open the grid of the master oscillator tube is connected through the resistors R_1, R_2, and R_3, the auxiliary switch coils *CS*, normally shorted by a $Z3$ back contact, and the resistors R_{CS} to the negative side of the battery. Under this condition the tube cannot oscillate. However, upon closure of any of the $Z3$ contacts or the ground start contact the grid is connected to the positive bus and the tube is thereby caused to oscillate.

The stopping of the carrier signal is controlled by the tripping contacts D and $Z2$ for phase faults and D_0 and I_{02} for ground faults. Closure of contacts D and $Z2$ energizes the auxiliary switch *CSP* which closes its contacts *CSP* one of which connects the point P to the negative bus. For phase faults carrier is started by $Z3$ contact which makes the grid positive and is stopped by *CSP* contact which connects the point P and with it the grid back to negative. However, if the ground start contact I_{03} also closes, for example, a phase to phase to ground fault, the point G and the grid are made positive and it is then impossible for the *CSP* contact to control the grid. In this case the carrier is stopped by the closure of the ground contacts D_0 and I_{02} energizing the *CSG* auxiliary switch to close the *CSG* contact which directly connects the grid to

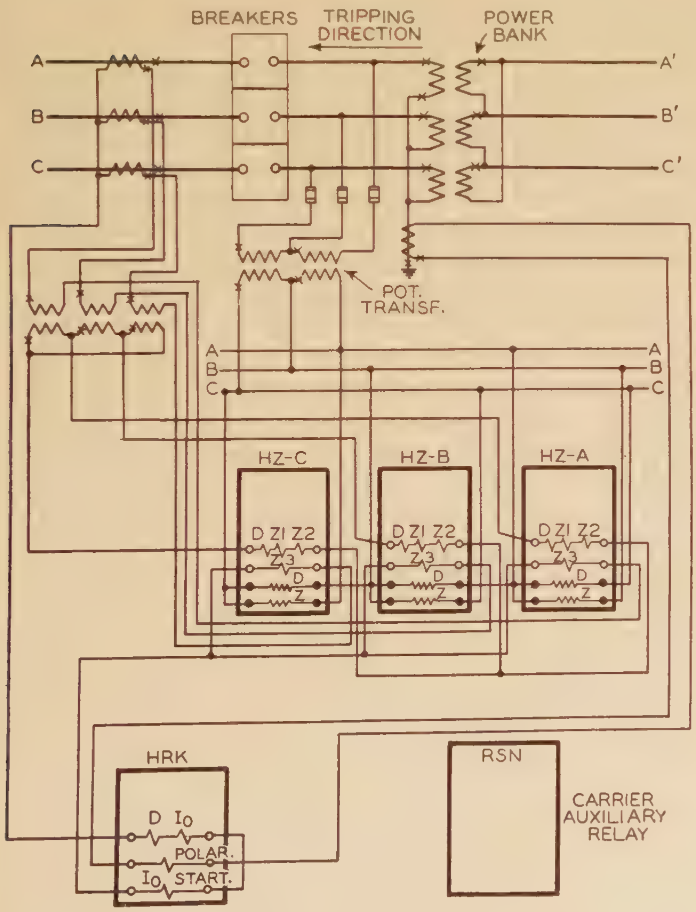

Figure 4. A-c schematic connections for distance-relay carrier scheme

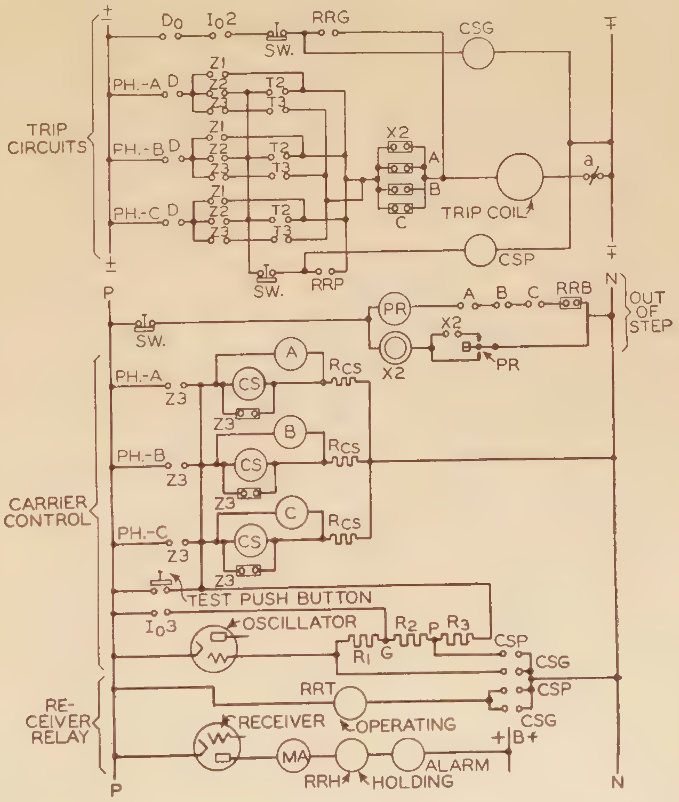

Figure 5. Schematic d-c connections of distance-relay carrier scheme

negative. Thus, it is seen that during faults involving ground, the action of the ground relays in starting and stopping carrier is given preference over the phase relays.

The purpose of this arrangement whereby the ground relays are given superiority in both the starting and stopping of the carrier signal is to prevent possible incorrect indications of the phase relays due to load currents and the flow of positive- and negative-sequence currents during external ground faults on systems with a multiplicity of grounding banks. On the other hand, in some cases it may be desirable to give the phase relays preference over the ground relays or to have no preference at all. Any one of these conditions can be obtained by a simple change in connections. If the grounding sources are of high impedance, the phase relay during an external fault may be operated in one direction by load current and the ground relays in the opposite direction at each end due to ground current. Without ground preference the line would trip out since each end has an internal fault indication. The use of single-phase directional elements with impedance supervision is very effective in reducing the possibility of load indication overriding faults on poorly grounded systems as only one-third of the load is opposed to the fault current on the active directional element. The ground preference scheme is provided in the standard system because most faults are grounds and it expedites ground clearing. The objection to ground preference action of blocking the phase relays in certain cases of 2 line-to-ground faults or simultaneous ground faults at 2 locations on a line does not apply to this system since the distance protection is still available to protect for this rare condition. Grounds are very frequent and authentic cases of simultaneous faults are rare. With 2-cycle relay time, they should be even more rare.

The carrier controlled blocking relay *RR* is a sensitive polarized d-c relay provided with 2 make contacts *RRP* and *RRG* and one back contact *RRB*. It is provided with an operating coil *RRT* energized by the local battery and a carrier holding coil *RRH* connected in the plate circuit of the carrier-current receiving tube. Normally, both coils are de-energized and the make contacts are held open by a magnetic bias. The relay is prevented from operating when the carrier holding coil is energized even though the operating coil is energized. Closure of the blocking contacts *RRP* and *RRG* can only be obtained by energizing the operating coil in the absence of the carrier signal. This relay is capable of very high speed, being able to close contacts in less than one-fourth cycle (0.004 sec.).

The complete sequence of events may be briefly summarized as follows: Assume an internal phase to phase fault just beyond the zone of the *Z*1 element. Carrier will be initiated immediately at both ends of the line by the closure of one of the *Z*3 contacts. Meanwhile, the directional and second-zone impedance contacts close and energize the auxiliary switch *CSP*, stopping carrier and energizing the operating coil of the carrier-blocking relay. Since the same action has occurred at the far end of the line, no carrier is received and the blocking contact *RRP* is closed completing the trip circuit through *D* and *Z*2. If the fault had been external to the section, then tripping could not have occurred, since the carrier holding coil *RRH* would have been energized by carrier from the far end.

If we assume a phase-to-phase-to-ground fault, the ground carrier start contact I_0 will also close, making the point *G* positive and it will be impossible for the phase relays to remove carrier through the *CSP* contacts. However, the ground tripping contacts (D_0, I_{02}) will close energizing the *CSG* auxiliary relay whose contacts can remove carrier.

Operating Time

Very satisfactory tripping times are obtained with this carrier current pilot relay scheme. The minimum times are, of course, obtained for faults within the reach of the *Z*1 elements and they are approximately 0.7 to 1.25 cycles (0.011 to 0.021 second). For faults in the end zones the tripping time is slightly longer because of the time consumed by the auxiliary element associated with the carrier and varies from 1.5 to 3.0 cycles (0.025 to 0.05 sec.), depending upon the magnitude of the short circuit current and voltage. The time consumed by the auxiliary switch *CSP* in removing carrier and included in the above time is approximately 0.3 cycle. This adds very little to the overall time in tripping, but during quick reversals of power where carrier must definitely be established at one end before it is removed from the other end of the line, this small time delay provides a positive margin of safety.

Contacts

In a circuit of this nature, in order to obtain the maximum speed of which the relay elements themselves are capable, it is necessary to remove as much of the contact bounce as possible. Current loading of the contacts is not permissible, since they are required to open the circuit themselves when the breaker is not tripped. These statements apply particularly to the *D* and *Z*2 contacts which must operate the *CSP* auxiliary switch and the *Z*3 carrier start contact and similar contacts on the ground relays. In order to eliminate contact bounce, it is necessary to employ some form of energy absorbing means and, of course, the preferable means is one which can absorb the energy continuously and not merely during the first blow. To accomplish this purpose the contacts and moving elements have been provided with a unique form of damping. The spring-mounted moving contact is in the form of a silver capsule partially filled with finely powdered tungsten. As the contact strikes the rigid stationary contact, the loosely packed tungsten particles slide over one another. The friction developed in the sliding of the tungsten particles very effectively absorbs the energy of impact and prevents the contacts from bouncing. In addition to the damping action of the tungsten powder in the moving contact itself, there is provided a cylinder of powder mounted directly on the beam of the impedance element to further eliminate vibration and prevent any vibratory energy being communicated to the contact itself. A similar arrangement is used on the directional element.

Out of Step

It is often desirable to prevent the operation of relays during out-of-step conditions as the system may pull back into step and if the system does not stabilize itself, it is then desirable to separate at locations where frequency control for synchronizing is available. The carrier signal between the 2 ends of the line provides a means of preventing tripping during out-of-step conditions without impairing the ability to trip with reasonable speed for internal faults occurring during out-of-step conditions.

The fundamental difference between a 3-phase fault and an out-of-step condition is that a fault suddenly reduces the voltages and increases the current, whereas during the approach of an out-of-step condition the voltage and current changes are comparatively gradual. For a 3-phase fault the distance elements are all operated practically simultaneously while during out of step the most sensitive distance element *Z*3 operates first, followed by *Z*2 and then *Z*1. As the system returns toward the in-phase position, the elements reset in the opposite order, that is, *Z*1, *Z*2, *Z*3.

To prevent tripping during out of step, it is only necessary to arrange for the closure of the 3 *Z*3 contacts and the receiver relay back contact to operate an additional blocking relay to open the trip circuit. This blocking relay must have a slight time delay so that it does not open the trip circuit before tripping on a 3-phase fault can occur. On the other hand, it must open the trip circuit during an out-of-step condition before the second element *Z*2 is operated. A time delay of 3 to 4 cycles (60-cycle basis) has been found satisfactory.

Referring to the schematic diagram figure 5, the out-of-step blocking contact is designated *X*2. In parallel with it are 3 contacts, *A*, *B*, *C*, which are the back contacts on the auxiliary switches *A*, *B*, *C*, operated by the *Z*3 contacts of the distance relays. The make contacts, *A*, *B*, *C* of these switches are in series with the back contact *RRB* of the receiver-blocking relay to energize the coil *PR* of a pendulum-type time-delay relay, whose lower contacts make and energize the coil of the *X*2 blocking relay. Every time that all 3 of the *Z*3 carrier start contacts close, the contacts *A*, *B*, *C*, and *X*2 open the trip circuit after 3 to 4 cycles. If the electrical center is inside the section, then when the two voltage sources are 180 degrees out of phase, the directional and impedance elements at each end of the line will be closed, removing carrier and allowing the contact *RRB* to open, de-energizing the pendulum relay *PR*. The blocking contact *X*2, however, does not immediately reset because its coil *X*2, is energized by the alternate closing of the bottom and top contacts *PR* due to the oscillation of the pendulum. After the amplitude of vibration of the pendulum has decreased to a certain value, it will not strike either of its contacts and *X*2 will reset. This time delay is adjustable and should be longer than the time during which both directional elements "point in," which depends upon the length of the "slip cycle" of the system.

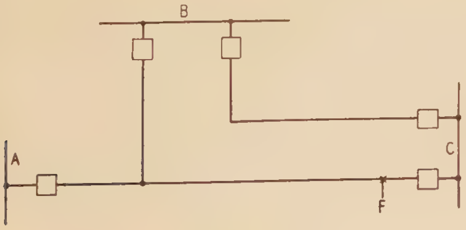

Figure 6

It is desirable to clear internal faults occurring during an out-of-step condition, but it is not so essential to be able to clear at high speed. The ground-relay trip circuit is not blocked by the out-of-step relay *X*2 and can, of course, trip instantly. On phase-to-phase faults one or 2 of the *Z*3 contacts will reset when the system swings in phase, thus allowing one of the back contacts *A*, *B*, or *C* to complete the trip circuit without waiting for the reset of *X*2. On a 3-phase fault, however, none of the *Z*3 contacts will reset and, consequently, tripping will not occur until after the expiration of the *X*2 time delay. The reset of *X*2 is made possible by the opening of the receiver relay back contact *RRB*. It will be noted from the diagram that the back-up tripping through *D*, *Z*3, and *T*3 is shown blocked by the out-of-step contacts in which case time delay back-up protection on 3-phase faults during out of step is not possible. It is arranged, however, so that the *T*3 connection can be made on the other side of the out-of-step contacts, and in this case tripping on out of step cannot be prevented for a period longer than the time setting of *T*3.

The *power supply* for the carrier set should be unfailing. This usually means battery supply with the high-voltage direct current obtained from either of 2 inverted rotary converters with automatic-transfer equipment, supplying 115-volt 60-cycle power to the power pack of the transmitter-receiver. Recent tube developments make possible a transmitter-receiver of moderate power operating directly from 125-volt battery, without power pack.

The *communication channel* for relaying must be reliable and for this reason wave traps or tuned choke coils are used. These choke coils insert enough resistance in the line to nullify the effect of impedance changes due to switching operations on the system. All taps or dead-end connection of noticeable length should be checked as an open line. One-quarter wave length long is a short circuit at carrier frequency. If *f* is the carrier frequency, the wave length is (186,000/*f*) miles for open wire line.

Supervision

It is desirable to periodically check the condition of the carrier set to determine its ability to send and receive a carrier signal. A means for accomplishing this manually is provided in the test push button connected in parallel with the carrier-start relay contacts. A milliammeter and an alarm element similar to the receiver blocking relay are connected in the receiver tube plate circuit. Depressing the test push button sends a carrier signal which operates the alarm relays at each end whose contacts operate a bell or other signal device. If the carrier set is not functioning, no signal is heard when the test push button is operated and this, of course, indicates trouble

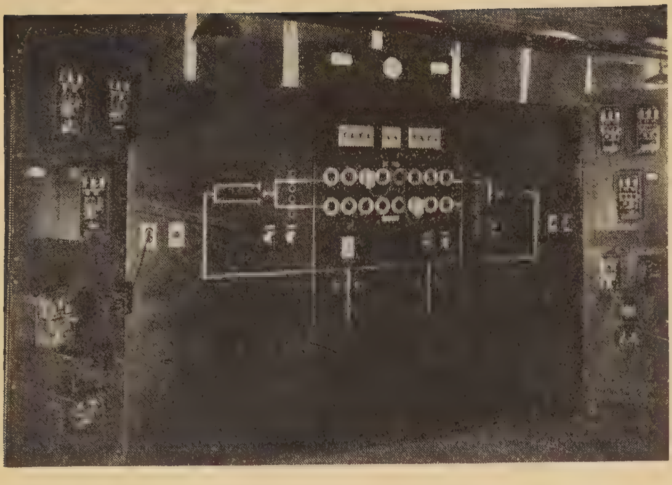

Figure 7. Two carrier-relay sets being tested on artificial transmission system

which must be investigated. The alarm receiver element has a minimum operating value in excess of the minimum value required to block the receiver relay from operating so that an indication of impending trouble can be obtained before actual failure occurs.

A periodic manual check every 8 hours is generally considered sufficient. However, if desired, an automatic periodic check can be obtained by arranging the necessary time delay relays to initiate carrier at one end of the line, transmit to the other end, and then re-transmit to the first end. If the carrier fails in either direction, an alarm is sounded.

Figure 6 is more or less typical of certain existing lines which must be protected. The application of carrier current protection alone to such a line will not operate in all cases, as the fault current flow may not be into the line at all three terminals. For example, with a fault at *F* and a high impedance source at *B*, a portion of the fault current will flow over the parallel line between *B* and *C*. The direction being out at *B* carrier will be transmitted, blocking all terminals. With distance protection added, breaker *C* will trip on the first zone setting and as soon as the breaker has cleared *B* and *A* will trip through the carrier relays This will be somewhat faster than the second zone time step of the impedance protection as there is no time added to allow for long time clearing. Tripping occurs immediately after the first breaker opens, while the timers must be set longer than the maximum relay plus arcing time.

The carrier starting element is required to start transmission on the occurrence of a fault in the range of the relay setting. For grounds either the line residual current may be used or grounding transformer neutral current. In the latter case, auxiliary switches on the breakers should be used to prevent starting when breaker is open, this is essential on three terminal lines where the line may be energized with one terminal open.

All through the development, the idea has been kept in mind to prevent tripping a good line and to clear a faulted line at the highest practical speed consistent with the above requirement. Greater tripping speed is possible, but with less security against errors. In the testing of various sets of equipment on the laboratory artificial line several hundred faults have been applied with no failures to operate correctly, which could not be traced to some defects in connection or associated apparatus.

Conclusions

1. Zone-arranged distance relays having separate impedance measuring elements for each zone contain inherently the necessary carrier controlling and tripping circuits for the intermittent-normally blocked carrier pilot relay system.

2. The zoned distance type carrier-pilot relay system affords the economic possibility of installing high-speed distance relays at one stage in the development of a project and adding the carrier later when simultaneous clearing of all faults is economically justified.

3. With the 3-zone impedance-type carrier-pilot scheme protection of the best type available prior to the carrier relay development is afforded during intervals when the carrier equipment is out of service.

4. Spare or "transfer" breakers equipped with this relay complement may be switched into use on carrier pilot or high-speed distance relayed lines using the same distance relays in either case.

5. The 3-zone distance-type carrier-pilot scheme having a first zone independent of carrier provides proper clearing in most cases of multiterminal lines where fault power may flow *out* at one or more terminals during an *internal* fault on the protected line.

6. Experience in over 2,000 installations of the zoned distance arrangement both with and without carrier pilot has shown it to be more flexible in obtaining selectivity of back-up protection with the balance of the system relaying, than any other known arrangement.

7. Greatest flexibility in testing arrangements and in substitution and addition of elements to meet individual system relay requirements is afforded by individual switchboard mountings of phase and ground relays and auxiliaries. This has proved generally more satisfactory than the mounting of all elements in a single case with greatly restricted availability of interelement connections for test and interconnection with special elements.

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Some Engineering Features of Petersen Coils and Their Application

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THE TUNED-REACTANCE method of grounding a system neutral was first disclosed by Professor W. Petersen of Germany in 1917 (German patent number 304,823). It has been used extensively in Europe and other parts of the world and the number of installations in the United States recently has been increasing rapidly, which suggests that there is a place for the Petersen coil in American grounding practice. Tracing briefly the installations of Petersen coils in this country, the first one was made in a 44-kv system in 1921. Operating records on this system showed that the Petersen coil had improved service considerably. A second installation of 2 coils was made in a 140-kv system in 1931. Again expected improvements in service were substantiated. Further installations were made in 33-kv systems in 1935 and 1936. Although favorable reports on service continuity were given on all these installations, up until 1937, a period of approximately fifteen years, only a total of five coils were installed in systems in the United States. During the same period approximately 1,700 Petersen coils were installed in systems in other parts of the world.

In recent months, 12 more Petersen coils have been purchased for installation in systems in various parts of this country. When these installations are completed, it will bring the total number of Petersen coils in the United States to 17, protecting more than 3,000 miles of line of voltages ranging from 33 kv to 230 kv. Further installations are being contemplated by operating companies. A summary of the various applications of Petersen coils in this country is listed in table I.

It is the purpose of this paper to discuss how electric service may be substantially improved with Petersen coils. Furthermore, a résumé of some of the practical design and application features of Petersen coils will be given, based upon the experience obtained from the previously mentioned installations.

The Place for the Petersen Coil in Grounding Practice

Possibly one of the reasons there is renewed interest in the Petersen-coil method of grounding a system neutral is the fact that it has proved to be a simple, effective, and relatively inexpensive means for eliminating the short-circuit currents and service interruptions usually associated with ground faults on overhead systems when the neutral is arranged in any other way.

It is generally known that a system operated with its neutral isolated from ground may be subjected to transient overvoltages due to arcs to ground during ground faults. Such a disturbance may not confine itself to the original faulty circuit but may spread to remote sections of the system and involve other phases. Experience has shown that the possibility of such trouble increases as system voltage and mileage increase. Grounding the system neutral solidly or through relatively low impedance will reduce the transient overvoltages, but in arranging the neutral in this way a momentary flashover to ground on one conductor becomes a short circuit which must be cleared by de-energizing the circuit. Thus, with either the neutral grounded or isolated, an interruption to service may occur.

The Petersen coil or tuned reactance method of grounding eliminates the transient overvoltages of the isolated neutral system and the short circuits of the grounded neutral system by extinguishing automatically the arc at the point of fault. Thus, one advantage of the Petersen-coil method of grounding from the viewpoint of those interested in maintaining service is that it eliminates the outages associated with flashes to ground usually encountered when the system neutral is otherwise arranged. Ground faults usually cause the majority of outages on overhead transmission lines as may be seen by referring to the latest report[1] of the subcommittee on grounding of the protective devices committee. This report gives information obtained from 27 systems which shows that the percentage of the total faults involving ground varied from a minimum of 30 per cent of a maximum of 97 per cent, with an average of 69 per cent. Thus, it may be reasoned that the elimination of the outages associated with ground faults will result in a substantial improvement in service on many systems.

Ground faults may be caused by lightning, wind, sleet, tree branches, birds, etc. A 5-year average of the probable causes of ground faults on systems ranging from 26 kv to 220 kv has been given in a recent AIEE paper.[2] It shows that 73 per cent of the ground faults are probably due to lightning and the rest to "other causes." The Petersen coil is capable of quenching flashes to ground from all transitory causes. It prevents the flash to ground from developing into a short circuit which disrupts service.

The Petersen Coil

The fundamental theory of the Petersen coil has been thoroughly treated in various papers. Therefore, this discussion will be limited to some of the practical aspects of an application.

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1. For all numbered references, see list at end of paper.

Table I. Petersen Coils in the United States

Power Company	Date of Installation	Number of Coils	System Voltage (Kv)	Approximate Miles of Protected Overhead Line	Line-Supporting Structures	Remarks
Alabama Power Company	1921	1	44	93	Wood poles	81 miles of overhead ground wire
Georgia Power Company	1929*	1	38	129	Wood poles and steel towers	97 miles wood poles, no ground wires
Consumers Power Company	1931	2	140	275	Steel towers	All but 40 miles of line without ground wires
Central Maine Power Company	1935	1	33	560	Wood poles	No ground wires
Public Service Company of Indiana	1936	1	33	160	Wood poles	No ground wires; 4,250 feet 3-conductor cable
Public Service Company of Denver, Colorado	1937	1	95	187	Wood poles and steel towers	31 miles of wood poles; 156 steel towers; no ground wires
Public Service Company of Indiana	1937	4	33	1,300	Wood poles	No ground wires.
Metropolitan Edison Company	1937	3	66	320	Wood poles and steel towers	127 miles wood poles; 194 steel towers
Public Service Company of New Hampshire	1937	1	33	120	Wood poles	No ground wires
Consolidated Gas and Electric Light and Power Company	1937	1	33	30	Wood poles	No ground wires; 3,000 feet 3-conductor cable
Southern California Edison Company	1938	2	230	260	Steel towers	2 overhead ground wires
	Total	17				

* Coil formerly on Alabama Power Company.

The quenching of an arc by the mechanical separation of contacts as in an oil circuit breaker is so universally used and understood that often a mental hurdle has to be cleared before it can be conceived that an arc can be extinguished otherwise. The Petersen coil puts out an arc without the aid of any moving parts by limiting the current in a flash to ground to a relatively few amperes and keeping the rate of rise of the recovery voltage low.

Theoretically, the leading charging current of the system is neutralized by the lagging inductive current from the coil which results in zero current in the fault. In practice, this is approximated as closely as conditions will permit.

The current in the fault consists of several components as shown in figure 1. Leading current is derived from the inherent capacitance in the lines, insulators, transformers, and other connected apparatus. Capacitance is usually considered to be a constant. Actually it has been observed to vary with weather conditions and corona. Measurements have been taken on a Petersen-coil-equipped system which show that the capacitive reactive current increased approximately 5 per cent during stormy weather. Corona also increases the charging current.

The lagging component of current comes from the Petersen coil. The coil reactance is high which permits the system neutral to be almost fully displaced during a ground fault.

With complete neutralization of the charging current, there is still a small amount of current remaining in the fault. This is an in-phase component of current and is derived from the resistance in the series and shunt paths in both the capacitive circuits and the Petersen coil. Corona loss will also increase the in-phase component of current. There is also harmonic current in the fault. The Petersen-coil impedance is too high for harmonic currents to return in any appreciable magnitude through the system neutral so they must return to the system through the system capacitance. On those systems which have installed Petersen coils to date, the third harmonic has been almost completely absent. The fifth harmonic has been present in some instances but there has been no occasion for compensating for anything other than the fundamental component of charging current. Harmonic currents of any appreciable magnitude higher than the fifth have not been observed.

The oscillogram on figure 2 shows the current in a Petersen coil and in the arc which was taken during a staged test on a 33-kv system. The harmonics are plainly visible in the arc current. System phase-to-phase voltages are also shown. It is to be noted that the fault produced no change in these voltages with the result that the connected load on the system was unaware of the disturbance.

Whatever fundamental frequency in-phase component of current is present in a ground fault is in phase with the line-to-neutral voltage of the faulty phase and is easily interrupted. In considering arc extinction, the magnitude of the residual current alone is not the only consideration. The magnitude of the recovery voltage at the time the current passes through zero is far more important. Should the current in a ground fault lead or lag behind the neutral voltage of the grounded phase by approximately 90 degrees, and an interruption be attempted at a current zero, there is full line-to-neutral voltage available to re-establish the arc. This condition obtains when the neutral is isolated or solidly grounded. If the fault current and voltage are in phase, the voltage phases through zero at approximately the same time the current does, and accordingly, the recovery voltage is low and the arc easily ex-

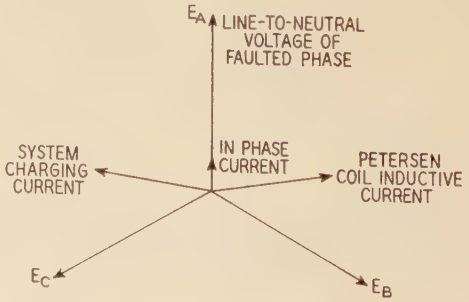


Figure 1. Vector diagram showing relation of the components of current in a ground fault on a system with Petersen coil

tinguished. This latter case occurs when a Petersen coil is in tune with a system. The significance of the part the recovery voltage takes in arc extinction may be demonstrated by staged tests on a Petersen-coil-equipped system by applying arcing faults with the coil detuned so that there is a predominance of either leading or lagging current in the fault as has been done on several occasions.

Successful arc extinction has occurred on a system[9] equipped with Petersen coils with the magnitude of the in-phase component of current as high as 50 amperes, and there is reason to believe that this current is not the outside limit that can be successfully handled.

Factors Influencing Characteristics of a Petersen Coil

The insulation on a Petersen coil is dictated by the voltage to which it is subjected. As it is a grounding impedor of special characteristics, designed for location between the system neutral and ground, it is subjected to dynamic neutral-to-ground voltages during ground faults.

In Europe, the Petersen coil has been insulated for the system line-to-line voltage and no protective equipment has been provided. In this country, Petersen coils have been insulated for system leg voltage and in addition, protective equipment has been furnished which is an integral part of the coil, consisting of either a station-type Thyrite lightning arrester or Thyrite resistor. An internal view of a Petersen coil showing the Thyrite resistor is given on figure 3.

Petersen coils installed in this country have all been constructed with iron cores except the one for the Alabama Power Company. This latter coil was a coreless reactor and service experience with it showed that it produced surges on switching operations, making it necessary to short circuit it during switching. It was found that unequal pole opening on one of the system oil circuit breakers put the coil and system into series resonance. Series resonance may tend to occur when there is an unbalance in the system voltage to ground, but no ground fault is present. Trouble of this nature has been entirely absent on all subsequent installations and was eliminated by constructing the Petersen coils with iron cores. These cores are specially designed to saturate on overvoltages. Saturation changes the coil reactance and destroys resonance.

The protective equipment included is for the purpose of rendering harmless the transient overvoltages which might reach the coil through the transformer in the neutral of which it is connected.

The current rating of a Petersen coil is established by the system charging current. The coil is designed to pass an inductive reactive current which is equal in magnitude to the system charging current in the 2 healthy conductors when the third conductor is grounded and the system neutral is at leg voltage above ground.

The charging current in a line-to-ground fault on a system is not subject to precise calculation as there are many factors to be considered which cannot be readily analyzed. The location of the equivalent ground plane; the effect of the supporting poles or towers on the transmission lines; substation structures, and trees along the right-of-way; the variation in sag, angles and bends in the lines, etc., and capacitance in connected apparatus, all influence the capacitance to ground and make it extremely difficult to predetermine exactly what the charging current will be.

Experience has shown that the charging currents calculated by the aid of Maxwell's coefficients should be used with caution, especially on the medium voltage lines. Measurements on several 33-kv systems have given charging currents as high as 50 per cent in excess of calculations for the line configurations in use. For medium voltage circuits with overhead lines, the measured charging current has varied between 4.8 and 6.7 amperes per 100 miles of line per 10 kv of voltage. For high-voltage circuits, Maxwell's coefficients have given the correct current within 10 per cent if corrections for corona are included.

Ammeter measurements of system charging current in solid conductor-to-ground faults will usually give currents in excess of requirements for the Petersen coil. Such measurement includes harmonic currents. The Petersen coil functions on the fundamental component of current only and accordingly due allowance must be made for the harmonic currents.

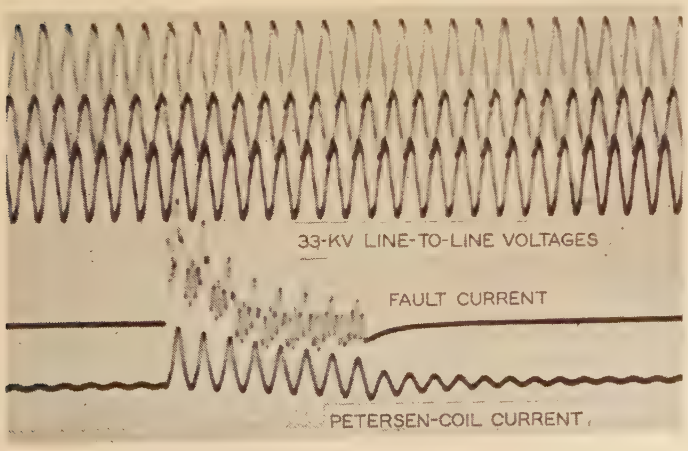


Figure 2 (left). Oscillogram showing the extinction of arcing fault by Petersen coil

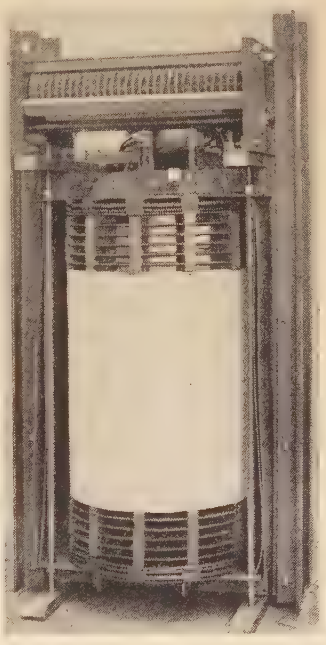


Figure 3 (right). Interior view of 33-kv Petersen coil showing Thyrite shunting resistor

The Petersen coil winding is tapped so that its inductive reactance may be matched with the capacitive reactance of the system. Additional taps are usually included so that variations in system capacitance resulting from switching or system growth may also be compensated. A current range on a coil greater than 3 or 4 to 1, however, is usually considered inadvisable because with a wider current range, a sufficient degree of saturation cannot be obtained in the iron core. If a greater range is required, 2 or more coils are recommended with the current requirements proportioned among them and provision made for switching them in and out of service as required. The taps on the coil are brought to a suitable position switch, the handle of which in the later coils is located on the side of the tank where it is convenient for adjustments as shown on figure 4. Taps are provided so that accurate tuning can be readily obtained. The number of these has varied in different coils from 10 to 25. The taps are so proportioned that the current output of a coil may be adjusted in increments varying between five and ten per cent of the current rating.

The thermal characteristics of a coil are usually established by whether or not the system has means for locating and segregating permanent ground faults. Petersen coils with 10-minute time ratings are recommended for systems that must remove all ground faults promptly. Time ratings shorter than 10 minutes are discouraged as a multiplicity of temporary faults may occur in rapid succession and overheat a shorter time rated coil. Petersen coils with continuous time ratings should be used where the ground fault is likely to remain on the system for a considerable time. Experience has also shown that when permanent faults have to be located by cut-and-try methods, time ratings of at least one hour are advisable.

Petersen coils are either furnished with conservators or gas-seals. A coil with a conservator is shown on figure 4.

General Application

Petersen coils may be applied to any transmission system or network. System voltage is no limitation on the application. Theoretically, one Petersen coil is sufficient to protect all parts of an entire system which are metallically interconnected. However, if the system is extensive, it is advisable to install several small coils rather than one large one. The combined current ratings of the coils should equal the total charging current of the system. With several coils located in selected sections of the system, the loss by switching a section out of service will not appreciably affect the protection for the remainder of the system. On systems with a limited number of miles of line, Petersen coils for compensation of charging currents under 5 amperes usually prove to be uneconomical.

Petersen coils may be applied to systems which are operated at present with the system neutral grounded or isolated. If the system neutral has been grounded, a check must be made to determine if all apparatus connected between the lines and ground, such as, for example, transformers and lightning arresters, are insulated for the system line-to-line voltage. Power transformers with graded insulation may be used with Petersen coils in their neutrals, provided the neutral insulation is suitable for line-to-neutral voltage. If the system neutral has been isolated, then usually there is little question but what the connected apparatus is suitable.

Petersen coils are designed for location between the system neutral and ground. The neutral of any convenient power transformer bank can be used for this purpose or, if none is available, grounding transformers will have to be installed. Attention should be called to the fact that during ground faults, the Petersen coil imposes an additional burden on the power transformer. This usually is not serious unless operation for extended periods is contemplated with one line conductor solidly grounded. In the latter case, a reduced power load on the transformer may be advisable; the exact amount to be specified by the transformer manufacturer. If grounding transformers are to be used, the additional burden imposed by the Petersen coil should be considered in determining its characteristics. On large networks, the use of a multiplicity of coils tends to decrease the Petersen coil burden on individual power transformer banks.

The exact location of a Petersen coil in an area to be protected is immaterial as far as the proper functioning of the coil is concerned. It is desirable, however, from an operating viewpoint, to have it in a centrally located position preferably where the transmission lines radiate to the various parts of the system so that the usual switching operations will not separate the coil from a major portion of the system.

Petersen coils will not function properly if the system on which they are installed is metallically connected to a solidly grounded-neutral system because the solid-neutral grounds in effect short circuit the Petersen coil. Likewise, an interconnection with an isolated neutral system requires retuning of the coil. Two systems, each properly compensated with Petersen coils can be interconnected without any adjustments of the coils. Tuning is not critical. On medium-voltage systems, different sections may be switched out up to possibly 25 to 30 per cent of the total mileage of the system and still obtain successful arc extinction without retuning for the new conditions.

Systems interconnected through autotransformers are in effect metallically connected together and if Petersen coils are to be used, they must be designed to compensate for the charging current of all the lines metallically connected to both sides of the autotransformers. It is inadvisable to use Petersen coils on such systems, however, if the transformation ratio of the autotransformer is appreciable because of the dynamic overvoltage that may be impressed on system apparatus during ground faults resulting from neutral displacement.

Systems with transmission lines of appreciable length of different voltage ratings on the same supporting structures may require special attention because of the mutual capacity effects between the lines of different voltage ratings.

Petersen coils should not be considered as a substitute for lightning protective equipment in substations and switch yards. It is a service rather than an apparatus protective device and should not be considered otherwise.

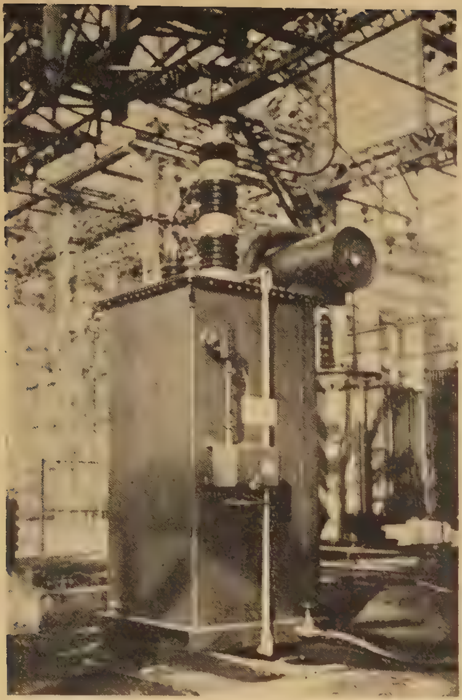


Figure 4. View of Petersen coil installed on 33-kv system

Petersen Coils and Ground Relays

An American solution of the arcing-ground problem has been to ground the system neutral solidly or through a relatively low impedance and install a selective system of ground relays. Consequently, the question is often raised as to the merits of applying Petersen coils to a system so equipped.

The addition of a Petersen coil will prevent the ground relays from functioning on all transitory ground faults, and thus eliminate many unnecessary line outages. If the fault is persistent, means may be provided for regrounding the neutral so that the ground relays can function to clear the faulty section. Thus, the Petersen coil may be considered to be a supplement to the ground relays; a device which prevents them from operating on all except permanent ground faults.

A small percentage of the ground faults on a system are a result of damage to the system insulation and must be located and segregated from the rest of the system by oil circuit breakers. The most positive way of locating such faults on a Petersen coil equipped system which has been proposed to date is to use a system of ground relays which responds to ground faults when the system neutral is directly grounded. The reactive current passed by a Petersen coil during a ground fault is insufficient to operate a selective system of ground relays but by arranging to bypass the Petersen coil and ground the neutral directly, when a permanent fault occurs, the relay system can be made to function when it is needed. This requires a suitable single-pole switch in parallel with the coil with control equipment which will close the switch after the ground fault has persisted for a definite predetermined time. Operating experience with Petersen coils to date indicates that approximately 15 seconds is ample time for a ground fault to clear if it is going to be extinguished automatically.

On a system grounded at one point, the relaying for ground faults is the simplest because the flow of fault current is all in one direction. The addition of a Petersen coil to such a system is a very simple procedure.

On a network grounded at several points, the relaying for ground faults becomes more involved because on occasions the network may be divided into sections. Neutral ground points should be located in each section if ground relaying is to be obtained under all conditions. For like reasons, Petersen coils should be located in each individual section of the system if protection is to be obtained at all times. On such a system, single-pole switches for short-circuiting the Petersen coils should be furnished for making the ground relays operative. Additional solid-neutral ground points over and above those in which the Petersen coils are located may be needed for selective relaying. Suitable switches in these neutrals functioning on zero-sequence voltage will provide these additional ground points. The far ends of radial feeders from a network may be relayed on zero-sequence voltage rather than zero-sequence current when there is an infeed of power at the far end. In this case a faulty radial feeder would clear in cascade, the near end first on residual overcurrent. This would leave the line with the neutral ungrounded for a brief interval of time, but the possibility of arcing grounds occurring is nil because the fault would be a direct ground.

In Europe, attempts have been made to relay on the uncompensated in-phase component of current in case of permanent ground faults. This requires a watt type of relay which is usually not very difficult to manufacture. However, as the magnitude of this in-phase current is small to begin with and varies with seasonal changes, the characteristics of the individual current transformers used with the relays must be matched very closely if selective relaying is to be obtained. The best information available indicates that these watt relays are used for fault indication rather than for tripping oil circuit breakers. On the occurrence of the fault, the station operators determine which feeder has relays that show an infeed of fault current at both ends. This circuit is then tripped by hand. This is also in keeping with the established practice in many parts of Europe of operating with one conductor grounded for considerable periods of time until it is convenient to remove the faulty feeder from the circuit. Operating with one conductor grounded for extended periods in this country will probably seldom be resorted to on overhead systems because of the possible hazards to safety, communication, etc.

Description of Systems on Which Petersen Coils Are Installed and Their Service Record

The Alabama Power Company Petersen coil was located on a 93-mile section of their 44-kv system. The lines were carried on wood poles, of which all but 12 miles were equipped with one overhead ground wire at the peak of the poles. All poles had down wires. During a period of slightly over 2 years this coil operated approximately 360 times, about 90 per cent of which were recorded as correct. The first year's operation indicated an 83-per-cent reduction in the number of interruptions over that obtained for the previous year.

This coil was kept in service about 4 years on this system. At the end of this time, the system outgrew the coil and it was removed from service. In March 1929, this coil was installed in the Marietta transmission substation of the Georgia Power Company's 38-kv system. This system has 129 miles of overhead line, 97 of which are wood poles without down wires or ground wires. On June 4, 1931, immediate initial reclosure was applied to the feeder circuit breakers. This company reports that the latter method of protection is so superior to any other method yet tried for improving service to radial feeders that little time has since been spent in analyzing the Petersen-coil performance, and data on its performance were not available at the time of writing this paper. It appears from other information sent us on this system that most of the tripouts from lightning resulted from phase faults and if this is the case, then the Petersen coil will prove to be of little use to them in improving service continuity.

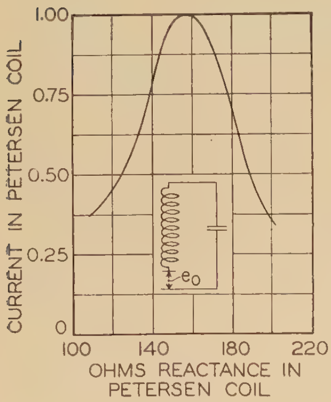


Figure 5. Tuning curve with no conductor grounded

The Consumers Power Company's 2 Petersen coils are installed on a 275-mile steel-tower section of their 140-kv system. All but about 87 miles of this system is single circuit and about 140 miles is without ground wires.

The operating record on this system shows that approximately 70 per cent of all the faults that occurred in 5 years' time were cleared without oil-circuit-breaker operation. In this period 242 faults were recorded with 171 extinguished by the Petersen coil.

The Central Maine Power Company's Petersen coil is installed on their 33-kv system. Five hundred and sixty miles of line of wood poles with pin insulators are protected with one coil. No overhead ground wires or down wires on the poles are used. In the first 14 months after installation, this coil operated 54 times and cleared all ground faults, which were not permanent faults, without a service interruption. On this extensive system, before the coil was installed, simultaneous faults in different parts of the system were quite numerous. Since the Petersen coil has been in service, this type of trouble has been mostly absent.

The Public Service Company of Indiana has 5 Petersen coils protecting more than 1,500 miles of 33-kv lines. These lines are supported on wood poles with pin insulators and, in general, are without ground wires or down wires. These coils are located in their Newcastle, Edwardsport, Lenore, Dresser, and Bedford Stations. The last 4 named coils, at the time of writing this paper, have not been in service long enough to have established a service record. The Newcastle coil has been in service for a longer period and the operating record has been watched with keen interest.

The 33-kv system in which the Newcastle Petersen coil is located is normally not interconnected with any of the other 33-kv lines. Approximately 80 miles of overhead line and 4,250 feet of 3-conductor cable constitute the usual operating set-up although on occasion a total of 160 miles of overhead line may be protected by the coil.

The operating record shows that 91 per cent of the faults on this system were cleared without a tripout. This operating record does not extend entirely through the severe part of the lightning season. Based on the record available, however, lightning caused approximately 25 per cent of all the faults. The ground faults which were successfully cleared resulted from wind, sleet, tree limbs, and lightning. This company reports that it is extremely well pleased with its Petersen-coil equipment.

The Public Service Company of Colorado has one coil in a 187-mile system operating at 95 kv. This line has 31 miles of wood poles and 159 miles of steel towers without ground wires. The neutral of this system was solidly grounded before the Petersen coil was installed. The operating record, month by month, on this system after the Petersen coil was installed, has been steadily improving. At first, a number of outages occurred which were apparently the result of somewhat defective insulation and incorrect relay operations. The latest monthly operating reports, however, indicate that these conditions have been remedied because approximately 73 per cent of all of the faults in these later months have been cleared by the Petersen coil. A detailed report of this installation has been given in a companion paper at this midwinter convention.[13]

The other installations of Petersen coils which have been made recently have not been in service long enough to have a report on their record. A summary of some of the system characteristics of these latter Petersen-coil installations, however, is given in table I.

The question is often raised as to the performance to be expected from a Petersen coil on a wood-pole line. The reasoning was that owing to the high insulation value of wood, most of the faults from lightning would involve more than one phase as the flashover potential between phases would be lower than from one phase to ground. The operating records on the several installations of Petersen coils on wood-pole lines previously mentioned show definitely that ground faults from lightning are obtained. One possible explanation of this is the fact that most wood-pole lines are guyed every few structures which provides a low-impedance path to ground. Also it is to be remembered that lightning is not the only cause of trouble. Studies, also previously mentioned, showed that lightning caused about three-quarters of all line interruptions and on medium-voltage lines, the proportion of faults attributed to lightning is often less. Although the operating experience with Petersen coils on wood-pole lines during lightning seasons has been good, the probability is that it would have been even better if every pole on the lines in question had down wires and low footing resistance.

Determination of the Optimum Tuning of a Petersen Coil

When a Petersen coil is installed in a system, it is necessary to match the inductive reactance of the coil with the capacitive reactance of the system. Taps are provided on the coil winding so that its reactance can be adjusted to meet the system requirements.

The proper setting of a Petersen coil may be determined by calculation if the charging current of the system has been accurately determined. Usually it is desirable to check at least one adjustment by test at the time the coil is put in service. These tests may be conducted during normal conditions (no conductor grounded) or with one conductor solidly grounded.

During normal conditions of operation, there is usually some slight unbalance in the system phase-to-ground voltages. This unbalance is sufficient to cause a small amount of current to flow continuously through the coil. For tuning tests, the coil ohms are varied and the current through the coil noted for each tap position. A typical plot of the coil current as a function of the ohms reactance in the coil taken on a 33-kv system is shown on figure 5. Correct tuning is obtained on the tap that results in maximum amperes.

The shape of this curve may be explained by understanding that the inductive reactance of the coil and the capacitive reactance of the system form a series resonant circuit with a voltage applied to it resulting from the normal system unbalance in voltage as shown on figure 5. When the coil is in tune with the system, the inductive reactance of the coil balances the capacitive reactance of the system so that the current flowing is at a maximum and is limited only by the losses in the circuit. The current diminishes as the coil is detuned because the impedance of the resonant circuit increases.

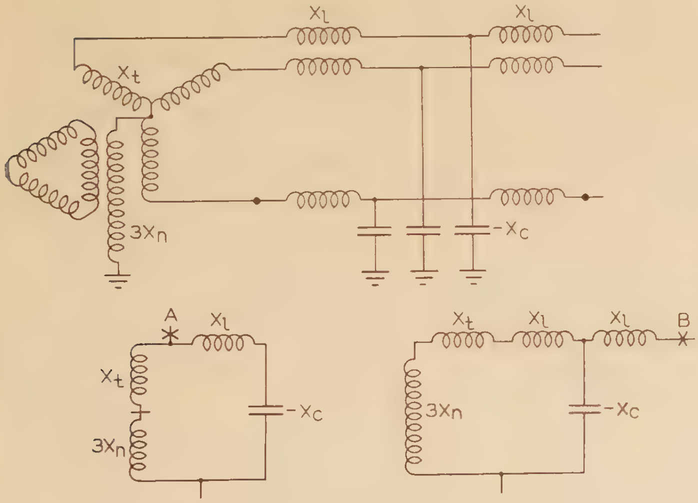
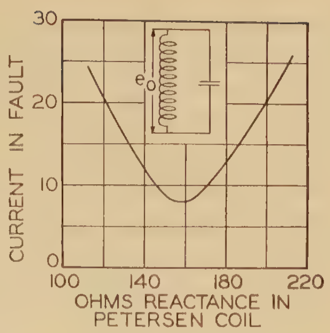


Figure 6. Zero-sequence impedance of Petersen-coil-equipped system with no ground fault

Figure 6A (lower left). Zero-sequence impedance for ground fault at (A)

Figure 6B (lower right). Zero-sequence impedance for ground fault at (B)

Figure 7. Tuning curve with one conductor grounded



For those familiar with symmetrical components, Petersen-coil action results when the zero-sequence impedance of a system is infinite. Accordingly, during ground faults, there will be no fault current in the positive- or negative-sequence impedance circuits and for calculations, the zero-sequence impedance circuit need only to be considered.

Tuning on normal unbalance in system voltage is expressed in symmetrical components by referring to the system zero-sequence impedance as represented on figure 6. Neglecting X_l and X_t which are small compared with X_n and $-X_c$ and designating the different capacitances to ground of the 3 phases as X_{c1}, X_{c2}, and X_{c3} the following equations may be written:

$$E + E_0 - I_{c1} X_{c1} = 0 \tag{1}$$

$$a^2E + E_0 - I_{c2}X_{c2} = 0 \tag{2}$$

$$aE + E_0 - I_{c3}X_{c3} = 0 \tag{3}$$

$$E_0 = -I_nX_n \tag{4}$$

$$I_n = -(I_{c1} + I_{c2} + I_{c3}) \tag{5}$$

$$I_n = \frac{E(X_{c2}X_{c3} + a^2X_{c1}X_{c3} + aX_{c1}X_{c2})}{-X_{c1}X_{c2}X_{c3} + X_n(X_{c2}X_{c3} + X_{c1}X_{c3} + X_{c1}X_{c2})} \tag{6}$$

tuning results when

$$X_n = \frac{X_{c1}X_{c2}X_{c3}}{X_{c2}X_{c3} + X_{c1}X_{c3} + X_{c1}X_{c2}} \tag{7}$$

When the capacitances of the 3 phases to ground are equal

$$X_n = \frac{1}{3} X_c \tag{8}$$

Tuning tests with one conductor solidly grounded are made by recording the current in the fault with the Petersen coil in different tap positions. The current in the fault is the resultant of the fundamental-frequency lagging current passed by the coil, and the leading charging current of the system, plus the in-phase components which result from leakage and harmonics. A typical plot of the fault current as a function of the ohms reactance in the coil is shown on figure 7. Correct tuning is obtained on the tap that results in minimum current in the fault as the lagging current passed by the coil just neutralizes the leading current of the system.

The shape of this curve on figure 7 results from the fact that with a line-to-ground fault on a system, the Petersen coil and the capacitance of the system form a shunt resonant circuit with a voltage equal to the system line-to-neutral voltage applied to it as shown on figure 7. With this type of circuit, resonance is obtained when the current in the fault is at a minimum.

The fault current may be expressed as

$$I_f = \frac{E}{X_0} \tag{9}$$

For a fault at the terminals of the transformer in the neutral of which the Petersen coil is located (location *A*, figure 6*A*) the zero sequence impedance is equal to

$$X_0 = \frac{3X_n(X_l - X_c + X_t)}{3X_n + X_l + X_t - X_c} \tag{10}$$

Varying the magnitude of X_n, a curve is obtained such as is shown on figure 7.

In equation 10 neglecting X_l and X_t, resonance obtains when

$$X_n = \frac{1}{3} X_c \tag{11}$$

This shows that provided X_c is a constant, either method of tuning gives the same tap position for resonance as may be checked by comparing equations 8 and 11.

Corona has the effect of increasing the effective diameter of the line conductors which in turn increases the system capacitance and when corona is present, a lower ohmic setting will be obtained for correct tuning during solid ground faults. When corona is present, the results obtained from fault tuning rather than those from the normal leakage current through the coil should be used.

It has also been observed that the system capacitance changes slightly with changes in the weather. It is known that the apparent capacitance of pin insulators increases when they are wet or covered with sleet. In all cases noted, these changes have caused a shift of less than 5 per cent in the tuning so it has been of little practical significance.

Tuning is independent of fault location. A Petersen coil in tune to a system for a ground fault at any particular location is correctly tuned for a ground fault at any other location. For a ground fault at the terminals of the transformer of the system (location *A*) shown on figure 6 the zero-sequence impedance is as given by equation 10. For a ground fault at the far end of the system at location *B*, the zero-sequence impedance is (figure 6*B*)

$$X_0 = \frac{(-X_c)(3X_n + X_t + X_l)}{3X_n + X_t + X_l - X_c} + X_l \tag{12}$$

Correct tuning is obtained when X_0 is infinite. This occurs when the denominator of equations 10 and 12 are zero. Since the denominators of the 2 equations are alike, correct tuning in both cases is obtained.

It is to be noted that as the ground-fault location progresses away from the coil, the impedance increases and the current through the coil decreases. The charging current also decreases in like proportion so that correct tuning is always maintained.

The question often arises as to the accuracy needed in tuning a Petersen coil to a system. Field tests have shown repeatedly that the best results are obtained when the coil is adjusted to within a few per cent of the exact tuning necessary. However, on medium-voltage systems, successful arc extinction has been obtained through a relatively wide range in reactance in the coil. Field tests on several 33-kv systems have shown that successful arc extinction would still be obtained if 25 to 30 per cent of the system was switched out of service. On high-voltage lines, a somewhat closer tuning is indicated to be desirable.

Summary

Service experience with Petersen coils on transmission systems and networks in this country has demonstrated conclusively certain facts concerning these protective devices which may be stated as follows:

1. There is definitely a place for Petersen coils in American system-protective practice.

2. The Petersen coil will prevent the interruptions to service usually associated with transitory flashovers to ground.

3. The Petersen coil may be applied to any system insulated for full neutral displacement.

4. Petersen coils do not lose their effectiveness if used on a system when different sections are switched out of service unless the system capacitance is changed more than 25 to 30 per cent.

5. Surges during switching operations encountered on the first Petersen-coil application have not recurred in later applications.

6. By the use of Petersen coils, it is possible that from 70 to 80 per cent of all faults may be cleared without the opening of a single oil circuit breaker, and without any dip in the phase-to-phase voltage, thus improving system stability and service continuity.

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The Thyratron Motor at the Logan Plant

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Introductory

THE QUEST for a simple variable speed a-c motor has been long and, heretofore, not particularly successful. Consequently ever since the thyratron motor was mentioned during the early years of the present decade, it has aroused a great deal of interest among engineers, both because of its operating principles and because it appears to offer the possibility of a really effective and economical variable-speed alternating-current drive. It has been of particular interest to central-station engineers.

Quite a number of types of a-c drive are in use today in central station service and many more have been designed and discarded or never applied. The difficulties of the problem have not been ones of principle. On paper it may appear easy to develop such a drive having a minimum of special parts or a minimum assembly of standard units. Yet when these are tried in practice, some apparently insignificant detail—an oil ring or a rotating bearing—develops unexpected trouble during operation and definitely limits the new design. The squirrel-cage motor has set a criterion in ruggedness and simplicity that it has so far been impossible to equal.

In central-station service, the tendency has been to reduce to a minimum the number of auxiliaries requiring variable speed. In recent years studies of heat cycle, indicating the desirability of using steam turbines for the larger auxiliaries have further limited the use of variable speed motors. Nevertheless, those auxiliaries which still require varying speed, such as boiler feed pumps and draft fans, are among the largest, from the point of view of energy consumption, in the plant. They also require the utmost in reliability and ease of control and because they are often on practically a 24-hour basis of operation, it is desirable that variable speed be obtained without sacrificing efficiency.

The reasons for adopting this type of motor were given in the *Electrical World* of July 6, 1935, and need not be repeated here. The advantages appeared sufficiently attractive so that the American Gas and Electric Company urged the completion of developments on this motor and were in close contact with the manufacturer as the work progressed. In a development of this kind, it is particularly essential that the operating requirements are clearly brought to the attention of the designers. Their concentration on the theoretical aspects of the problem sometimes leads them to overlook homely but nevertheless important details. Dust tight distributor and tube compartments, safety interlocks on tube cells and cubicle doors, segregation of power and control terminals in the cubicle, forced air cooling, overspeed device, tube removal under load, and tube failure alarm are examples of the results of this co-operation. As in all new designs many minor difficulties arose which had to be overcome but nothing which could be considered basic.

Description of Equipment

The motor is rated 400 horsepower, 2,300 volts, 3-phase, 60-cycles, 40 degrees centigrade and was designed to drive an induced draft fan having a speed range from 625 to 350 rpm. It closely resembles a standard synchronous motor with a rotating field, except that it has two independent star-connected stator windings installed in the same slots. Unlike a synchronous motor, however, the field terminals, after being brought out through slip rings, connect to the neutral points of the star windings. As shown in figure 4, the six remaining power leads connect in a special arrangement to a series of 18 type *FG*-118 thyratron tubes, each having a continuous rating of 12.5 amperes and a maximum rating of 75 amperes.

The accessory equipment includes a three-phase current-limiting reactor, a thyratron-tube cubicle, and a speed-

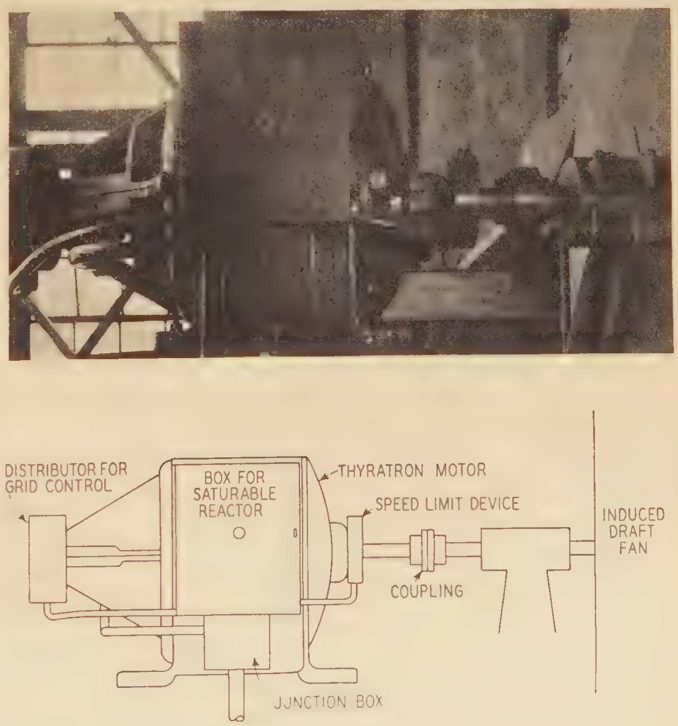

Figure 1. Thyratron-controlled 400-horsepower motor, Appalachian Electric Power Company—Logan plant

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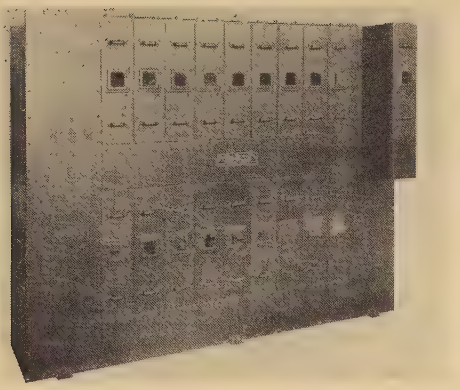

Figure 2. Thyratron cubicle showing spare tube compartment, Appalachian Electric Power Company—Logan plant

control panel. Each tube is mounted in an individual removable cell so as to facilitate replacement during operation. Tube cooling ducts and blowers, heater and grid transformers, and other accessories are all assembled within the cubicle.

The speed-control panel contains a small wound-rotor motor functioning as a phase shifter for the purpose of effecting the desired speed changes. On this panel are also mounted a line ammeter, the 2,300-volt primary oil circuit breaker control switch and the auxiliary power control switch. The motor, cubicle, and speed-control panel are shown in figures 1, 2, and 3 respectively.

Accessory Devices

The 18 thyratron tubes consume about three and one-half kw at full load with another one and one-half kw consumed in the various auxiliary transformers and relay coils in the cubicle. Forced air cooling is used to dissipate the tube losses. The air stream is directed at the base of the tubes and leaves at the top. For winter operation, the cooling system is operated partly closed and is supplemented by strip heaters. In the summer time it operates entirely open and without the heaters. Thermostatically controlled dampers regulate the output of the strip heaters as well as the proportion of recirculated and fresh air.

About 800 watts are consumed in excitation losses in the stator of the small wound-rotor motor which acts as a phase shifter for speed control, but since this is mounted on the speed-control panel which is remote from the cubicle, it does not contribute to the heat generated there. The 220-volt auxiliary power totals to about 57 kilowatt-hours in a 24-hour day, this load remaining practically constant regardless of motor load.

A series of 18 glow lamps, excited from small current transformers in the cathode circuits serve for remote indication of tube performance. In addition, a relay energized through a tuned circuit, connected across a saturable reactor in the motor field circuit rings a bell to indicate abnormal tube firing.

A cathode timing relay is used to insure preheating of the cathodes for approximately 15 minutes before the 2,300-volt oil circuit breaker can be closed.

Figure 5 shows the distributor which is mounted on the motor shaft to obtain commutation of energy between thyratron tubes. The distributor segments are connected to the grids through intermediate transformers. Two sets of segments are used, one for normal speed and a supplementary set effective at low speed by utilizing the inherent commutating action of the three-phase power supply to obtain a high starting torque. Transfer between sets is made automatically at about 150 rpm by means of a relay operating from a current transformer in the stator circuits.

An ingenious arrangement of current transformers is utilized to act on the grid circuits and cause a phase shift independently of the speed controller and thus limit tube current. Due to this feature the motor can be accelerated from standstill to a preset speed by throwing it directly across the line without danger of damage. It is thus inherently self-protecting, the overload relays on the oil circuit breaker acting solely as backup protection. Only twice rated full load current is taken under this condition.

For best operation the cathode heater potential should be lowered slightly as the load increases, since this tends to maintain a constant tube temperature. This is accomplished by inserting one winding of a saturable reactor in series with the heater circuit, the other winding being in series with the motor field. A third or saturating winding is excited from direct current. This saturable reactor serves a dual purpose, its other function being to initiate an alarm when a tube fails, as mentioned above.

Tube Disconnecting Feature

During the development of the control equipment it became evident that facilities would have to be provided for tube replacement while the motor was in operation. Since the anode potential is 2,300 volts, safety to personnel had to be taken into consideration. Means had also to be provided for interrupting the anode supply before the tube was removed and this required a 2,300-volt disconnecting switch capable of interrupting the normal tube current, since it was not considered advisable to interrupt

Figure 3. Speed-control panel for thyratron-controlled motor, Appalachian Electric Power Company—Logan plant

the anode circuit at the separable contacts of the individual tube cell. This presented a problem on account of the limited space available. It was successfully solved by developing the fuse type of disconnecting switch shown in figure 6*A*. The circuit is interrupted from the outside of the cubicle by the key which unlatches the door. The individual cells cannot ordinarily be unlocked without opening the respective disconnecting switch. However, when all tubes are to be inspected while the motor is out of service, a master key permits access to all of the cells without releasing the disconnecting switches. A thyratron tube with filament continuously heated is kept available at all times in a spare cell. (See figure 2).

Operating Principles

The operating principles of the motor have been fully described elsewhere (Electrical Engineering, November 1934). For the sake of completeness a brief review with reference to figure 4 may be helpful.

The motor, although structurally resembling a synchronous machine, functions like a d-c series motor and has characteristics closely resembling such a machine. The field winding and each phase of each stator winding are traversed by a direct current, although like values of current in the stator coils differ in time phase.

A thyratron is a mercury-vapor hot-cathode rectifier tube. A positive grid voltage is essential to start the tube conducting, but once the current flows, the grid has no further effect and conduction will continue until the anode becomes negative with reference to the cathode. If the applied grid voltage is alternating, a shift in phase between the anode and grid voltages will delay the initiation of anode-current flow, decrease the amount of energy passed during the positive half cycle, and hence decrease the speed of the motor. From this it should be clear that the motor speed is independent of system frequency.

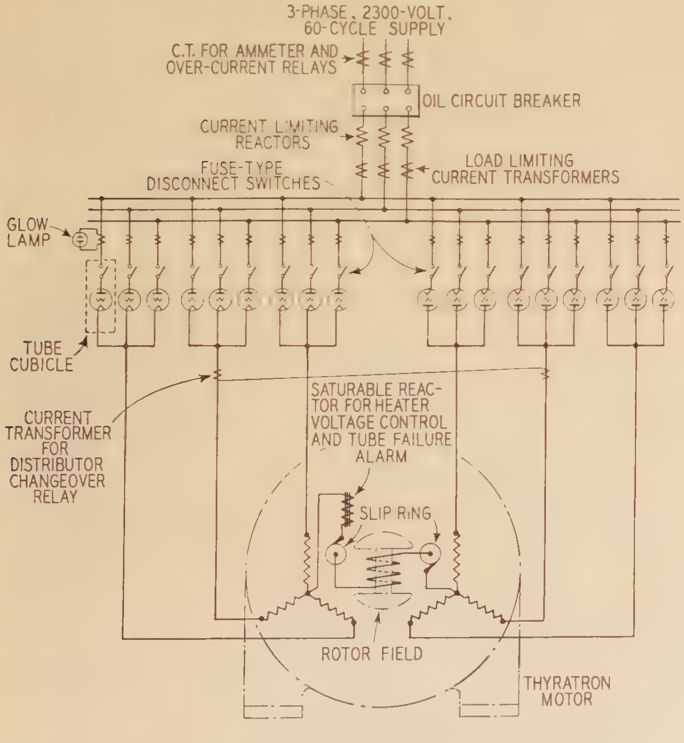
3-PHASE, 2300-VOLT, 60-CYCLE SUPPLY
C.T. FOR AMMETER AND OVER-CURRENT RELAYS
OIL CIRCUIT BREAKER
CURRENT LIMITING REACTORS
FUSE-TYPE DISCONNECT SWITCHES
LOAD LIMITING CURRENT TRANSFORMERS
GLOW LAMP
TUBE CUBICLE
CURRENT TRANSFORMER FOR DISTRIBUTOR CHANGEOVER RELAY
SATURABLE REACTOR FOR HEATER VOLTAGE CONTROL AND TUBE FAILURE ALARM
SLIP RING
ROTOR FIELD
THYRATRON MOTOR

Figure 4. Power connections for thyratron-controlled motor, Appalachian Electric Power—Logan plant

An open grid circuit will prevent tube conduction; therefore a distributor mounted on the motor shaft and connected into the grid circuits can control the time of firing of the tubes as a function of rotor position. Thus "commutation" can be attained. By connecting in parallel three tubes which receive their supply from a three-phase source, polyphase energy may be utilized for one stator phase subject to the control of the distributor. If the phase shifting and distributing features are connected in series, any tube can be controlled to fire at the proper time and for a desired interval. Thus commutation and controlled rectification with concomitant speed variation may be obtained within a single tube.

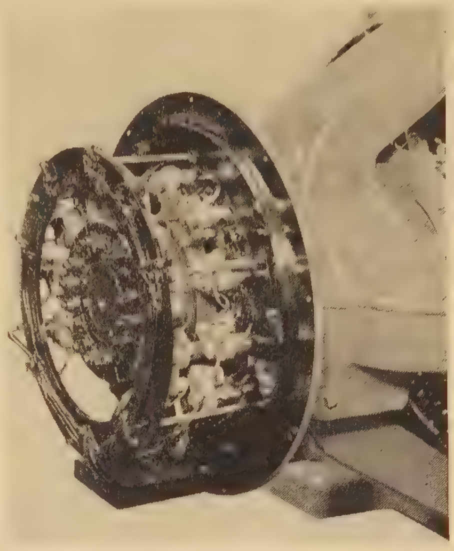

Figure 5. Distributor on thyratron-controlled motor, Appalachian Electric Power Company—Logan plant

Installation Considerations

Figure 7 shows a typical arrangement of connections between the motor and its control equipment. It is evident that there is an advantage in keeping the cubicle close to the motor. However, it is also necessary that it be installed in as cool a place as possible in order to limit the tube temperatures to the recommended upper limit of 55 degrees centigrade.

The air taken into the cubicle should be cool and clean as a deposit of dust may lessen creepage distance and lead to a failure of equipment. All covers in the cubicle must be sealed tightly to prevent dust gaining access to parts having inherently small clearance to ground. At the time of this writing it is planned to relocate the cubicle at Logan to a cooler place because the tube temperatures are close to the recommended limit.

Experience has indicated the desirability of having the cubicle base mounted on resilient supports in order to minimize shock. Rubber mounting pads under the four corners are being used for this purpose.

Since the motor has characteristics similar to a d-c series motor, precautions against loss of load, however remote, must be taken and a speed-limit device interlocked with the primary breaker control should be installed. An additional safeguard is provided in a limit stop which is placed on the speed control dial so that the rated speed cannot be exceeded. (See figure 3.)

The saturable reactor previously described is mounted directly on the motor frame and enclosed in a sheet metal box, thus avoiding the use of additional high voltage power connections. It is recommended that the distributor selector relay be also mounted in this cabinet, thus materially lessening the number of control wires between the motor and cubicle.

Spare Parts

Since there are 18 duplicate tubes with their accessories, the number of different types of device is not very large and consequently the number of spare parts to be kept on hand is rather limited. These include grid condensers, protective gaps, resistors, fuse-type disconnecting switches, copper-oxide rectifiers, grid and filament transformers, distributor brushes, blower motor, and a quantity of thyratron tubes. Most of these items cost very little; the thyratron tubes, however, are still rather expensive.

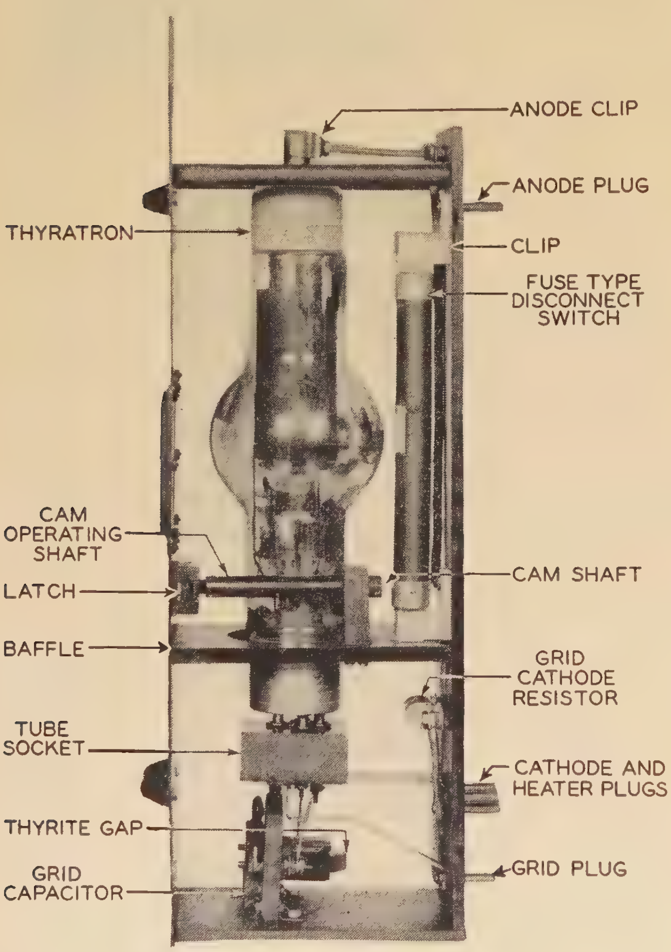

Figure 6. Thyratron tube cell showing 2,300-volt fuse-type disconnect switch

The door latch rotates the eccentric thus releasing pressure on a flat copper contact strip. The spring retracts the conductor through a section of fuse powder, thereby breaking the circuit. This switch can be used indefinitely since the conductor does not ordinarily fuse—only a slight pitting appears at its tip after a number of operations. To recondition, an operation similar to refilling a standard fuse is required, taking only a few minutes

Table I. Thyratron Tube Failures, May 29, 1936 to July 31, 1937

Failure Number	Tube Service Hours of Operation	Time of Failure	Nature of Failure
1	191	While starting	Cathode heater burned open
2	679	While starting	Cathode heater burned open
3	787	While starting	Cathode heater burned open
4	1,079	During preliminary heating before starting	Cathode heater burned open
5	2,362	During preliminary heating before starting	Cathode heater burned open
6	2,862	While starting	Cathode heater burned open Grid destroyed
7	792	During preliminary heating before starting	Cathode heater burned open
8	3,576	During operation	Apparent short circuit in tube. Protective gap and capacitor destroyed
9	4,509	During operation	Cathode heater burned open
10	4,628	During preliminary heating before starting	Cathode heater burned open
11	5,440	During operation	Tube ceased firing for no apparent cause
12	5,829	During preliminary heating before starting	Cathode heater burned open
13	5,829	While starting	Tube ceased firing for no apparent cause
14	3,550	During operation	Tube ceased firing for no apparent cause
15	6,400	During operation	Cathode heater burned open
16	742	During preliminary heating before starting	Cathode heater burned open
17	7,106	During operation	Cathode heater burned open
18	2,053	During operation	Interior of tube completely destroyed
19	7,560	During operation	Tube ceased firing for no apparent cause
20	8,272	During operation	Cathode heater burned open

Operating Experience

There have been so many references in the technical press to the pioneer installation of the thyratron motor as to lead to the belief that it has been running for a long time although it was actually placed in regular operation at the Logan power station of the Appalachian Electric Power Company on May 29, 1936.

During the year the motor has been in operation at this writing, a comparatively large number of minor difficulties arose. Yet in spite of these, the plant operators are very enthusiastic about its performance. Experience has shown them that no drive compares with it for ease of control, for smoothness of draft regulation, for ability to rotate at very low speed, and for almost entire elimination of fan blade maintenance expense. In view of the fact that plant operators are pretty hard-headed and tend to look with suspicion on new "gadgets," this response would seem convincing evidence of its success from a practical standpoint.

The most serious difficulty has been with the thyratron tubes themselves. In 14 months of operation, 20 tubes have failed, almost all of them due to the opening of the cathode heater circuit. Table I summarizes these failures and table II troubles from other causes. It is to be noted that the actual hours of motor operation represent a service availability of 84 per cent. This includes shutdown from all causes such as boiler and fan maintenance. Interruptions due to the motor alone took only three and one-half per cent of the operating time and an availability of $96^1/_2$ per cent may be considered a not unsatisfactory record for an entirely new type of control.

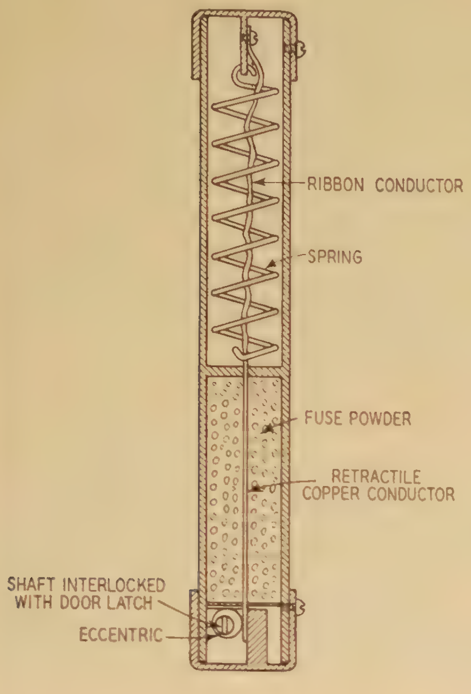
RIBBON CONDUCTOR
SPRING
FUSE POWDER
RETRACTILE COPPER CONDUCTOR
SHAFT INTERLOCKED WITH DOOR LATCH
ECCENTRIC

Figure 6A. 2,300-volt fuse-type disconnect switch for thyratron-controlled motor

Table II. Operating Troubles With Thyratron Motor Accessories, May 29, 1936 to July 31, 1937

Failure Number	Interruption Time—Hours	Cause
1		Filament transformer burned out
2	192	Field coil burned out
3	84	Field coil burned out
4	$^1/_2$	Fuse type disconnect switch burned open
5	20	Ground on one stator phase due to cable rubbing against dowel pin
6		Fuse type disconnect switch pulled apart
7	$1^1/_2$	Protective gap and grid capacitor destroyed
8	$^1/_2$	Thyratron tube and protective gap destroyed
9	$3^1/_2$	Fuse type disconnect switch arced to ground. Replaced. Again arced to ground. Replaced
10	4	Ventilating fan motor burned out
11		Field coil showed evidence of charring
12		During boiler shutdown, new set of field coils installed, and bearings changed
13		Fuse type disconnect switch burned open
14		3 tubes fired irregularly. Brush on distributor made poor contact
15		Bearings worn due to erratic magnetic center Evidence of electrolysis causing bearing pitting. Corrected by placing brushes in contact with both ends of shaft, connecting together and grounding

Total: 306 boiler-hours lost.
Total hours of operation: 8,376.

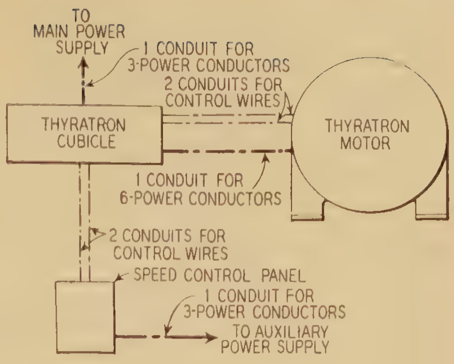
TO MAIN POWER SUPPLY
1 CONDUIT FOR 3-POWER CONDUCTORS
2 CONDUITS FOR CONTROL WIRES
THYRATRON CUBICLE
THYRATRON MOTOR
1 CONDUIT FOR 6-POWER CONDUCTORS
2 CONDUITS FOR CONTROL WIRES
SPEED CONTROL PANEL
1 CONDUIT FOR 3-POWER CONDUCTORS
TO AUXILIARY POWER SUPPLY

Figure 7. Thyratron-controlled motor—typical arrangement of equipment and conduits

Discussion of Operating Troubles

Many of the difficulties encountered are of a nature which would make it extremely improbable that they will be encountered again. For instance the trouble with three field coils was evidence that the motor field was being subjected to unexpected surge voltages and that its original insulation was inadequate. When the entire set of coils was replaced by ones having greater insulation, no further trouble of this type manifested itself.

The pitting of the bearings and the unexpected thrust due to unbalanced magnetic forces causing excessive bearing lining wear and coupling troubles were completely cured by the installation of brushes bearing on the shaft and connected to ground.

Failure of parts due to arcing to ground have been corrected where possible by providing greater clearance and the experience gained from this can of course be incorporated in subsequent designs. The fuse-type disconnect switches leave some room for improvement but they were an afterthought in the initial installation and probably a better type of device will be available for subsequent installations.

The grounding of a stator phase lead by rubbing against a metal dowel pin could have occurred in any machine.

Auxiliary transformers, protective gaps, resistors, condensers, blower motors, etc., are always possible sources of trouble. Filament and grid transformers operate at 2,300 volts and clearances must be kept large to avoid creepage due to infiltration of conducting dust which is always present in a power plant. No doubt some of the smaller devices will occasionally fail from time to time, but they are comparatively inexpensive to replace and mostly of such a nature as not to cause an immediate shutdown in case of failure. Even these can be improved by careful attention to the requirements.

The thyratron tubes leave the biggest room for improvement. A large number of failures has resulted either while starting or during the preliminary heating period and tube designers should consider these facts. Without a doubt the fragility of the cathode heaters can be corrected. The very persistance of this type of failure should be a clue to the remedial measures necessary. Steps have already been taken in this direction by the use

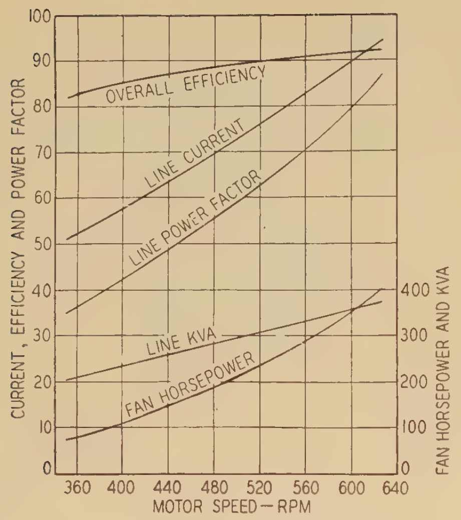

Figure 8. Performance characteristics of thyratron motor as determined by test

of flexible instead of solid connections at the cathode heater terminals within the tube.

Operation With Defective Tubes

Although defective tubes are replaced almost immediately during operation, it is interesting to note that no harmful effects occur if several tubes cease firing simultaneously. During factory tests as many as four tubes were removed simultaneously in various combinations, from different parts of the circuit, the only noticeable effect being a drop in speed and a slight irregularity in rotation. The motor will even start single phase (six tubes removed) although, of course, it will not attain full speed under this condition.

Tests were made with the cathode heater supply and grid control circuits suddenly interrupted to simulate blowing of fuses. Speed remained normal during the 15-second interval permitted by the cathode timing relay before shuttting down the motor. Low primary voltage, sudden opening and closing of the primary breaker, and almost all possible combinations of interruption of main and auxiliary power supply were tried without any noteworthy change in operation except a decrease in speed or irregular rotation due to unbalanced torque. It would go hard with any operator who attempted at the plant any operation even remotely resembling the paces that the motor was put through at the factory. Although the characteristic curves obtained from test were published previously (*Electrical World*, July 6, 1935), they are given here (figure 8) for ready reference.

Conclusion

Whether the thyratron motor is here to stay would seem to depend to a considerable extent on the tube designer. The operating principles of the motor are fundamentally sound; the control will undoubtedly be improved and simplified. This should aid in reducing the first cost of the motor to a competitive level, but tubes must be made more rugged if maintenance costs are not to be excessive.

A New Single-Channel Carrier Telephone System

By H. J. FISHER
Membership Application Pending

M. L. ALMQUIST
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On OPEN-WIRE lines where the growth is not rapid, there is frequently need for adding telephone circuits one at a time. When the type-*D* single-channel carrier telephone system was developed a few years ago it became possible to meet this need without stringing additional wires.[1] More than 500 of these systems have been placed in service in the Bell System plant. A new single-channel carrier telephone system, known as the type *H*, has recently been developed and is now being applied. This new system offers improved performance, and also, because of its lower cost, is applicable to providing service over shorter distances than were economical with the earlier system.

The type-*H* system, which is characterized by a number of new features and special developments, is applicable not only to the needs of telephone companies but also to those of railroads, power systems, and oil companies.[2] In the first place it is designed to operate either on a-c or on d-c plate and filament supply. A repeater is available to extend the range of operation. Through the use of specially designed but simple filters the system can be employed on circuits which are equipped with bridged telephone stations at intermediate points as is frequently the case in railroad operation.

A unique feature is the use of opposite sidebands of the same carrier frequency for opposite directions of transmission. The upper sideband is used in one direction and the lower sideband in the other, the carrier being suppressed. For the modulators and demodulators copper-oxide "varistors" are employed in place of vacuum tubes. The amplifiers are single stage, employ pentode tubes and are stabilized in performance by feedback. The filters are simplified in construction by the use of coils with a new type of core material and by improved designs of paper condensers.

The size of the new terminal has been so reduced that it occupies less than 40 per cent of the space required for a type-*D* terminal, as indicated in figure 1. The equipment may be mounted on racks as is customary in telephone offices, or a complete terminal or repeater may be mounted in a small cabinet.

Single-channel carrier systems have been used in the Bell System principally for short open-wire toll circuits. Thus, the type *D* systems are for the most part between 50 and 200 miles in length. The type-*H* system, since it includes a repeater can be used for greater distances, and due to its lower cost is economical for shorter distances.

General Description of System

Basic System

The basic system consists of two terminals one of which is refered to as an "east" terminal and the other as a "west" terminal, as indicated in figure 2. The two terminals differ only in minor respects, the differences being due to the fact that at one terminal the upper sideband is transmitted and the lower sideband is received, while at the other terminal the reverse takes place. In order to simplify co-ordination between various types of carrier systems operating on the same pole line, the frequencies between 7,400 and 10,150 cycles are transmitted in the east to west (or north to south) direction, and the fre-

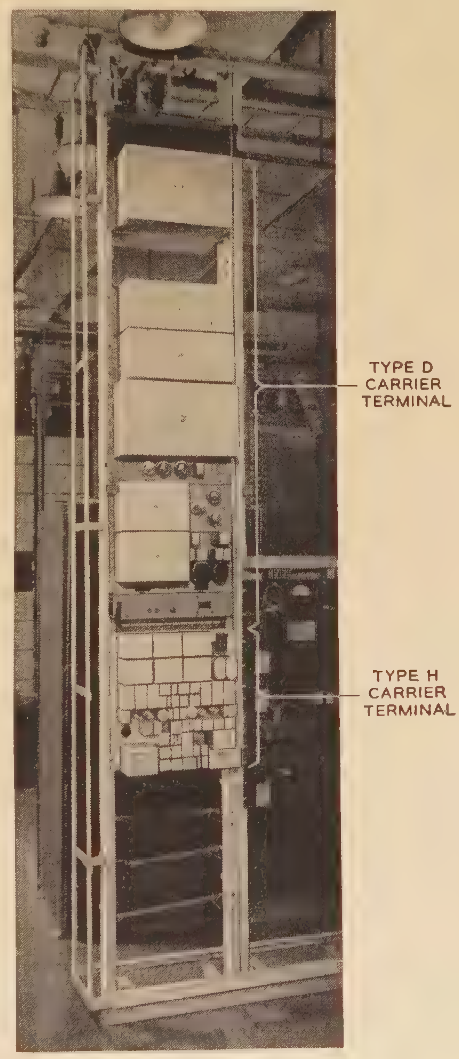

Figure 1. Installation of type-H carrier telephone system at Charlotte, N. C.

A paper recommended for publication by the AIEE committee on communication, and scheduled for presentation at the winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted September 13, 1937; released for publication October 30, 1937.

H. J. Fisher, M. L. Almquist, and R. H. Mills are all members of the technical staff of Bell Telephone Laboratories, Incorporated, New York, N. Y.

[1] For all numbered references, see list at end of paper.

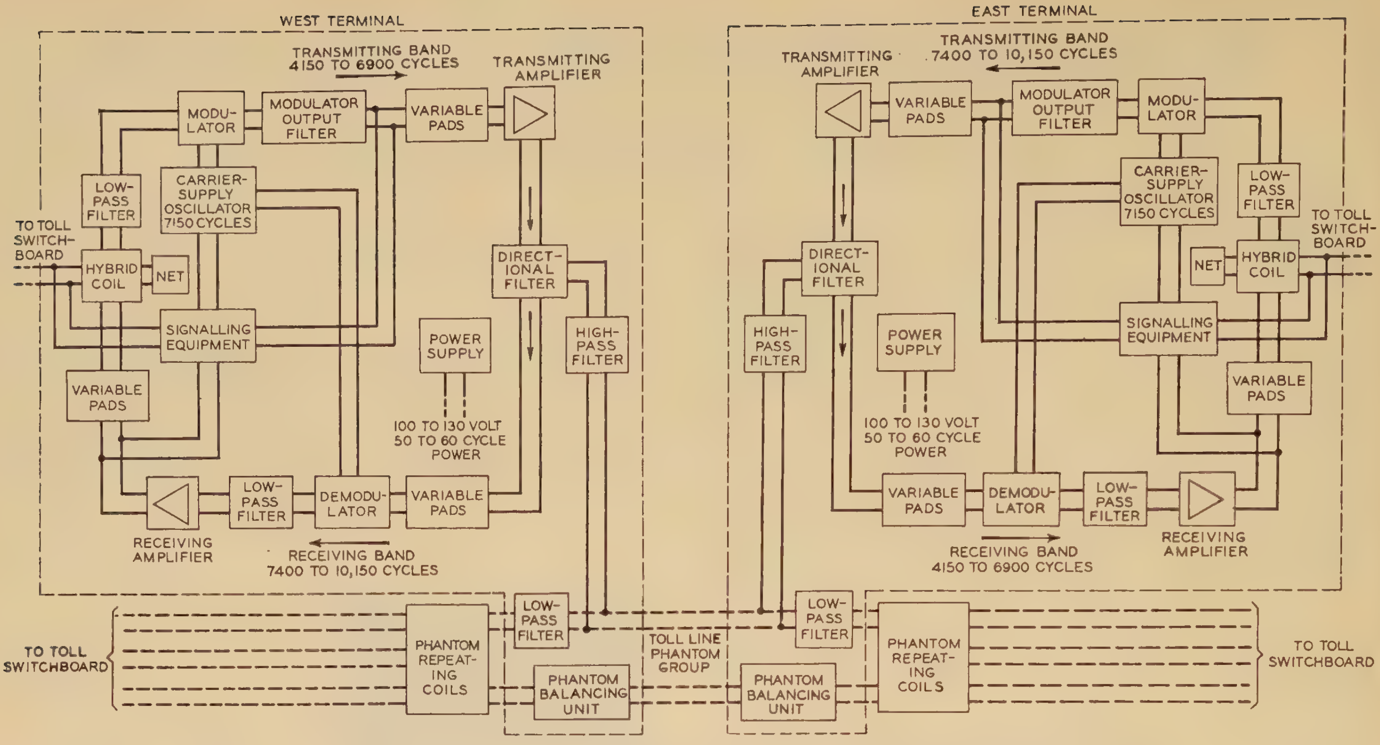

Figure 2. General schematic of type-H system applied to side circuit of phantom group

quencies between 4,150 and 6,900 cycles in the west to east (or south to north) direction. The frequency allocation of the type *H* system and those for the type-*D* and the three-channel type-*CS* system are shown in figure 3. All three types may be operated on the same pole line.

The circuit arrangement is given in greater detail in figure 4, which shows a schematic diagram of one terminal, with the exception of the power supply circuit. Each terminal is made up of a transmitting branch which includes a modulator, a receiving branch which includes a demodulator, and a hybrid coil to combine the two branches into a two-wire voice frequency circuit. The carrier is generated by a vacuum tube oscillator which supplies both the modulator and demodulator. The output of the modulator, which is of the copper-oxide type, consists principally of the two sidebands. The desired sideband is selected by the modulator output filter and an amplifier raises the level to that desired for transmission over the line. The demodulator is also of the copper-oxide type; its output consists principally of the two sidebands, one of which is a reproduction of the original voice-frequency input. This is selected by means of a low-pass filter and applied to a voice-frequency amplifier which provides the necessary receiving gain. Adjustable pads serve as a means for adjusting the transmitting and receiving gains. The characteristics and functions of the various filters are described later.

For signaling over the carrier circuit, a 1,000-cycle signaling system is employed. The method is similar to that used on other types of circuits, but includes a number of simplifications. The number of tubes has been reduced, and the vibrating relays used in the older type circuits have been replaced by copper oxide rectifiers and simple d-c relays requiring little maintenance. When 20-cycle ringing current is received from the switchboard the frequency of the carrier supply oscillator is shifted by 1,000 cycles and its output is interrupted at a 20-cycle rate, and applied to the input of the transmitting amplifier. At the receiving end this appears at the input of the signal receiving circuit as a 1,000-cycle current interrupted at a 20-cycle rate. It is then demodulated in a copper-oxide rectifier and the resulting 20-cycle current is amplified and applied to a second rectifier the output of which is connected to a d-c relay. Operation of this relay causes 20-cycle current from a local source to be sent toward the switchboard. Freedom from false operation on speech is obtained by tuning the receiving circuit to the rate of interruption and by providing a slow operating relay such that the signal must persist for several tenths of a second before 20-cycle current is passed to the switchboard.

The power supply circuit, which is shown in figure 5, operates from an a-c source of 100 to 130 volts, 50 to 60 cycles and requires about 50 watts. It supplies a-c for the filament supply, 160 volts d-c for plate supply and 24 volts d-c for relay operation. Provision is also made for direct operation from 24-volt and 130-volt central office batteries.

The equipment for a terminal is mounted on two panels. One of these, shown in figure 6, is $15^1/_4$ inches by 19 inches in size and contains all the apparatus except the line filter circuit. The second panel, shown in figure 7, is $3^1/_2$ inches by 19 inches and contains the line filters, and other equipment which is required for balancing purposes.

Repeater

A schematic of the repeater is shown in figure 8. The amplifiers are the same in design as the transmitting

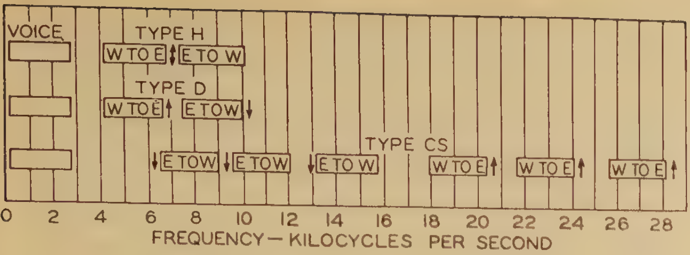

Figure 3. Frequency allocation

amplifier at the terminals. Two sets of line filters are required, and are identical with those used at the terminals. The a-c power supply circuit is substantially the same as the one used at the terminals except that the 24-volt supply for relay operation is omitted. The power required for operation is about 35 watts.

The complete repeater consists of three panels—the repeater panel, which is $10^1/_2$ inches by 19 inches, and two line filter and balancing panels. The repeater panel is shown in figure 9.

Transmission Performance

Line Considerations

In outlining the transmission performance of the system, it is necessary to consider the characteristics of the lines as well as those of the equipment. At carrier frequencies the line losses and the variations in these losses with weather are considerably greater than at voice frequencies. This is illustrated in figure 10 which shows the attenuation-frequency characteristics for four commonly employed gauges of open-wire line under dry and wet weather conditions, respectively, at a temperature of 68 degrees Fahrenheit. These curves are for 12-inch spaced copper wires equipped with the type of insulators ordinarily employed for toll circuits. Changes in temperature also affect the attenuation, the loss increasing as the temperature rises. The variations due to changes in temperature are, however, smaller than those due to changes from dry to wet weather and are more likely to occur gradually. It is apparent that the variations in attenuation with weather increase with the length of the system, and that more frequent adjustments will be required on the longer systems to maintain the over-all circuit net loss within given limits.

The carrier frequency attenuation of cable circuits is much greater per unit length than that for open-wire lines. Hence, the losses introduced by comparatively short sections of cable, either at entrances to offices or at intermediate points are of considerable importance. In addition to the attenuation of the cable itself, there are large reflection losses at the junction of the cable and the open wire, due to the difference between the characteristic impedance of the open wire and that of the non-loaded cable. The carrier terminal and repeater have been designed to have the same impedance as the average of the open-wire line facilities, so the same considerations apply

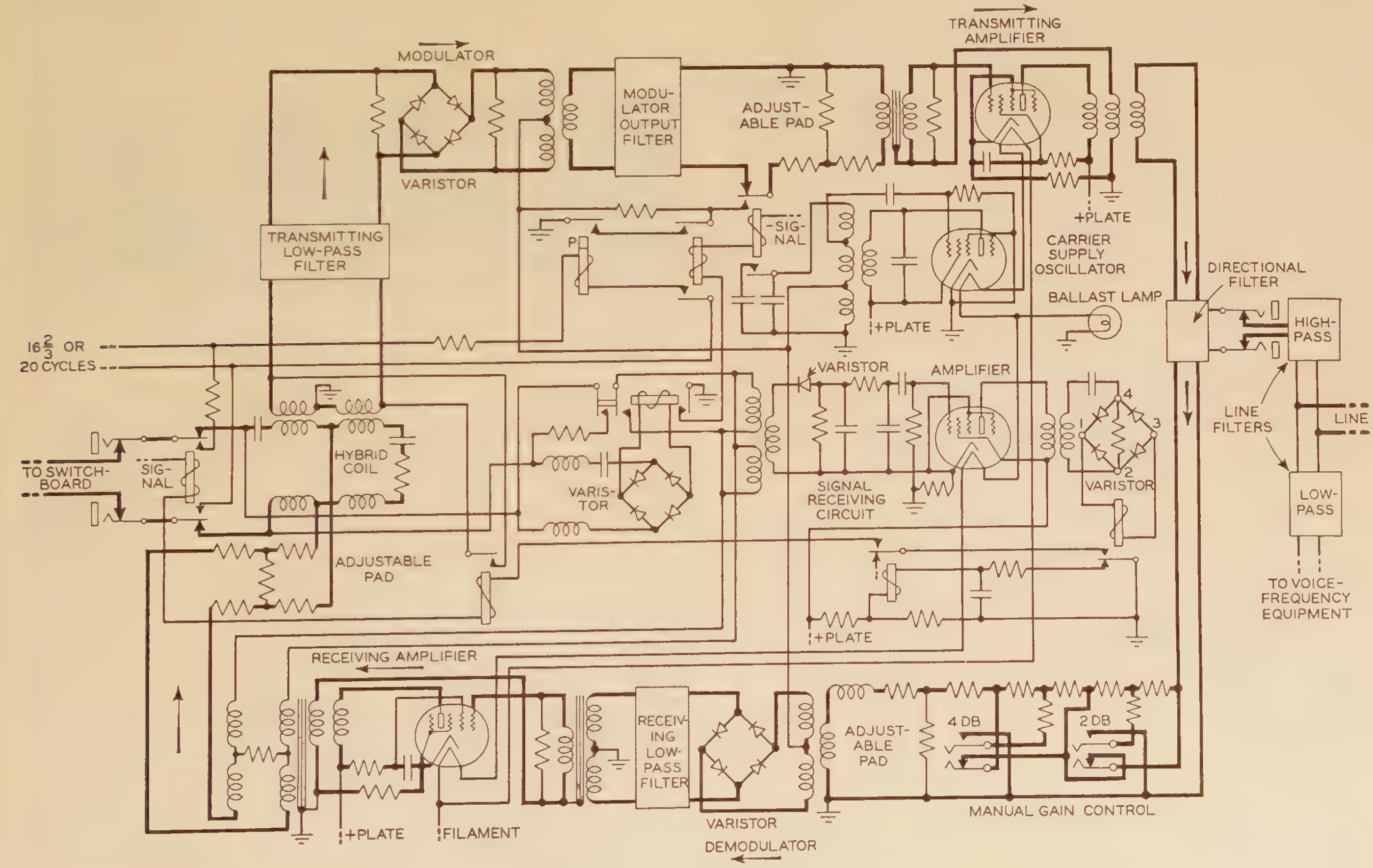

Figure 4. Schematic of type-H terminal

at the junction of the cable and the carrier equipment. As an example of the magnitude of these effects, the insertion loss at 8,000 cycles of two miles of non-loaded 16-gauge cable is approximately 6 decibels, or about the same as that of 60 miles of 104-mil open wire.

By applying carrier loading that has been developed for this purpose, the attenuation loss of such a cable can be reduced to about one decibel at 8,000 cycles. In addition, the reflections at the terminals of the cable will be reduced to satisfactory low values by virtue of the impedance matching properties of the loading. This method of treatment has the important advantage that it improves the transmission characteristics in both the voice and carrier range.

In cases where substantial transmission margins exist, it is sometimes practicable to use impedance matching transformer networks at the cable terminals, as a substitute for carrier loading, with economies that are proportional to the length of the cables. At the present stage of development, this so-called transformer treatment is much less satisfactory in the voice-frequency range than in the carrier-frequency range. Certain inherent limitations in simple transformer treatment result from the fact that the ratio of the (non-loaded) cable impedance to the open-wire impedance varies widely over the frequency band to be transmitted, and the transformer impedance ratio that is optimum at carrier frequencies is distinctly disadvantageous in the voice frequency range. The choice of optimum transformer ratio for the complete transmission band may thus involve different compromises for different sets of conditions and service requirements.

Where several carrier systems are to be placed on a pole line, crosstalk between systems becomes an important consideration. Where only a few single-channel systems are involved, it is sometimes possible, by separating the systems widely on the pole line, to operate with only the regular voice-frequency transpositions, but, in general, additional transpositions are required. A comparatively inexpensive transposition system for this purpose was designed at the time the type-*D* system was developed. It permits operation of type-*H* systems on all pairs of a four crossarm line with the exception of the pole pairs, and type-*C* three-channel systems on the top crossarm. In addition to transposing it is important that reflections at junctions between open-wire and cable be reduced as described above, in order that near-end crosstalk will not through reflection appear as crosstalk at the distant terminal of the system.

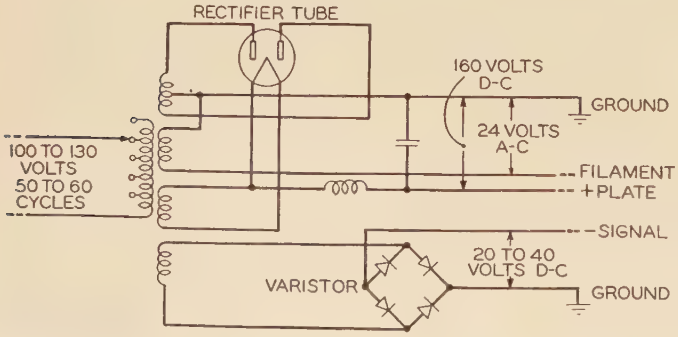

Figure 5. Schematic of a-c power supply for terminal

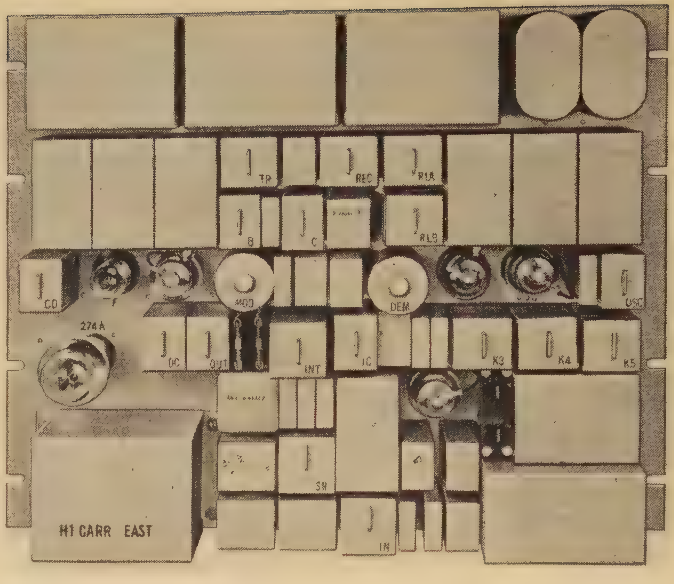

Figure 6. Terminal panel—front view

RANGE OF OPERATION

The terminals and repeaters have sufficient load carrying capacity so that they may be operated at an output level 16 decibels above that at the transmitting toll switchboard. About 19 decibels transmitting gain and 14 decibels receiving gain are available at each terminal, of which a total of 20 decibels may be used at the east terminal and 22 decibels at the west terminal. The lower permissible loop gain (sum of transmitting and receiving gain) at the east terminal is not controlling, since the line loss is greater for the frequencies used in the east to west direction than for those used in the west to east direction. Thus, the terminals are capable of providing a 9-decibel circuit over a line whose attenuation does not exceed 31 decibels at 8,150 cycles and 29 decibels at 6,150 cycles. These figures correspond roughly to the wet-weather attenuation of about 280 miles of 104-mil open wire where no intermediate cable or equipment is involved. The presence of even a small amount of cable will considerably increase the attenuation so that in most cases, the distance which can be spanned is not greater than 150 to 200 miles, and may be even less.

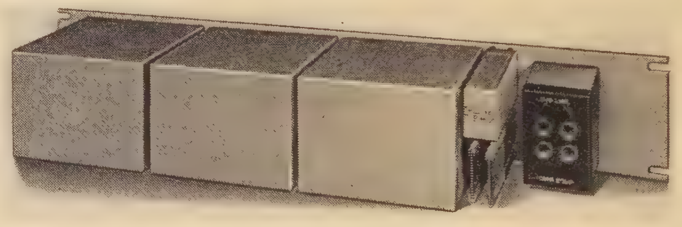

Figure 7. Line filter and balancing panel—front view

Where greater distances are to be covered, an inter-

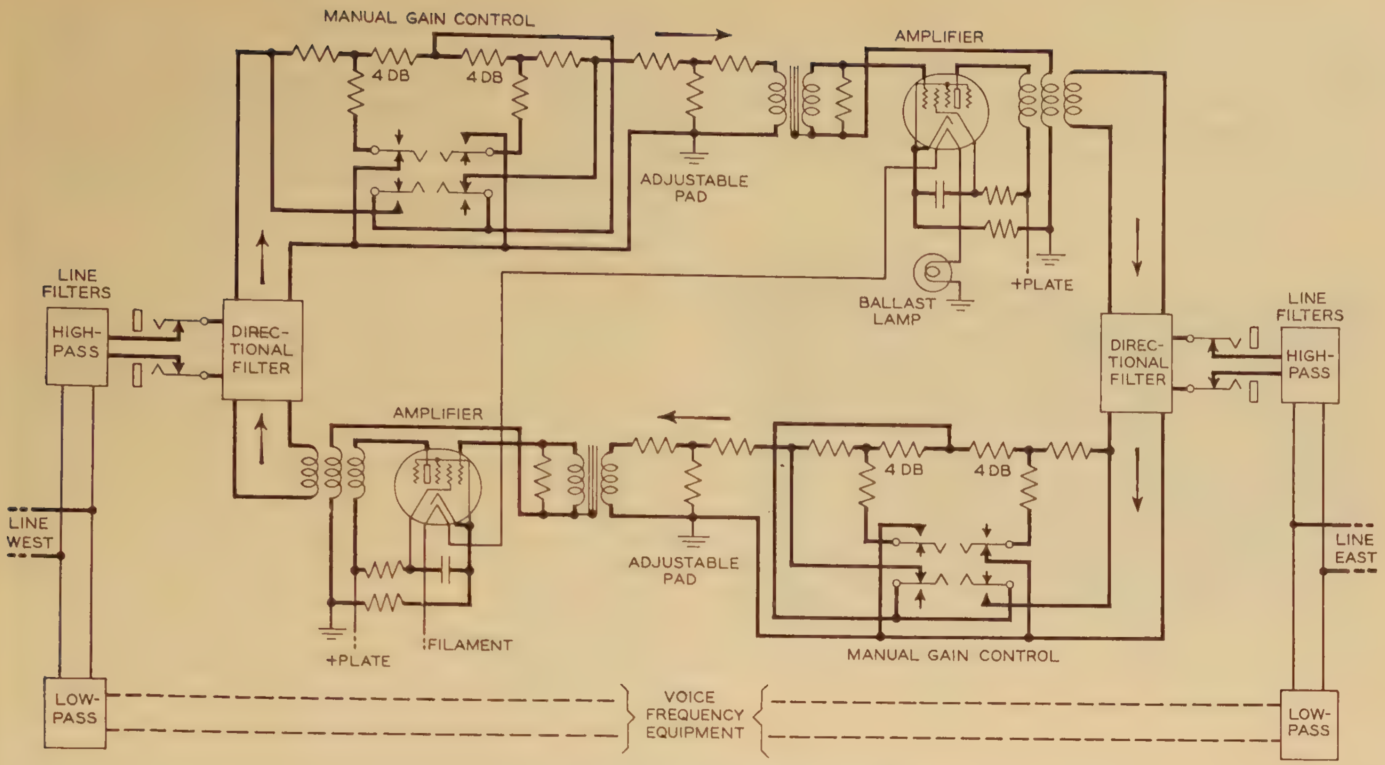

Figure 8. Schematic of repeater

mediate repeater may be added. The repeater has a useful gain of about 23 decibels in each direction, with some flexibility as to allocation of gains between the two directions of transmission. More than one intermediate repeater can, of course, be employed, although as the system is lengthened maintenance effort will be increased, as more frequent adjustments of the over-all net loss will be required to compensate for the variations in line attenuation with weather. No provision is made for a pilot channel such as is generally provided on the long multichannel systems, and adjustments of over-all net loss must be made manually. Also, no provision has been made for equalizing the variation in line attenuation with frequency. These factors are not important on the shorter circuits for which the system has primarily been designed.

OVER-ALL TRANSMISSION CHARACTERISTICS

The circuit provided by a type-*H* system without a repeater has a band width of about 2,750 cycles, extending from about 250 to 3,000 cycles. This is somewhat wider than that for the type-*D* system. The introduction of repeaters will tend to narrow the band somewhat. Representative frequency characteristics are shown in figure 11. One set of characteristics is for a typical circuit without a repeater, and the other for a circuit including two repeaters. It is assumed that the line conditions are such that no large reflection effects are present.

The band width is limited principally by the characteristics of the band filters. The small differences in the characteristics for the two directions of transmission are due partly to differences in the filters and partly to the fact that the attenuation of the line increases with frequency and is greater at the 3,000-cycle point in the east-to-west channel than for the 3,000-cycle point of the west-to-east channel. As the circuit is increased in length this difference tends to increase.

Variations in over-all circuit net loss are due largely to variations in the loss of the high frequency line. For a circuit 200 miles long these may amount to ± 3 decibels. The key-controlled pads which are included at each terminal and repeater are provided for making adjustments to compensate for these variations. Variations due to the equipment are small in comparison with the line variations. The transmitting gain at a terminal may vary ± 0.5 decibel and the receiving gain ± 0.3 decibel for variations of ± 10 volts in the a-c supply. With a more stable a-c supply or when operated from regulated plate and filament batteries such as are employed in the larger telephone offices, these variations will be less than half the figures given above. With suitable maintenance it should be possible to maintain the over-all circuit net loss within ± 2 decibels of its normal value.

A representative load characteristic, as measured with 1,000-cycle current for a system without a repeater is shown in figure 12. On a repeatered system some additional limiting of high inputs may occur. However, even on repeatered systems, there should be no noticeable distortion for input volumes such as are obtained directly from a switchboard.

REACTIONS ON VOICE-FREQUENCY CIRCUIT

In superimposing a carrier system on a voice-frequency circuit, line filters are added to provide separate paths for the voice and carrier circuits. The introduction of a filter in one side of a phantom group requires the addition of a network in the other side of the phantom group to maintain the balance of the phantom circuit from a noise and crosstalk standpoint. It is also necessary for return loss reasons to balance these units in the network circuits of voice-frequency repeaters that may be located at the same point as a carrier terminal or repeater. The networks required to take care of these conditions are included with the carrier system.

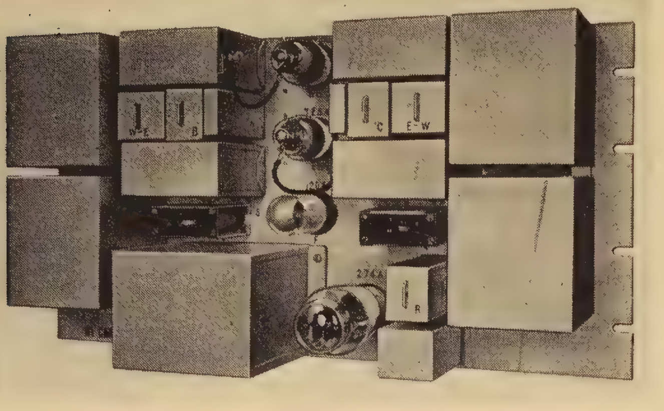

Figure 9. Repeater panel—front view

In some cases it is desired to apply the type-*H* system to circuits equipped with bridged telephone stations at intermediate points. Such arrangements are common on railroad communication systems, and occur to a small extent in the Bell System. In such cases, excessive interference into the carrier system due to talking at the way station, and into the way stations due to talking on the carrier system, is likely to occur unless suitable filters are provided at each way station. A simple filter for this purpose has been developed for use with the 501-type subscribers set, and work is proceeding on a similar filter for use with other types of subscribers sets.

The line filters and the filters for use at way telephone stations each introduce a loss of about 0.15 decibel to the through voice-frequency transmission. Where the voice-frequency circuit is equipped with repeaters and return loss conditions permit, these additional losses may be taken care of by readjusting the voice-frequency repeater gains. In extreme cases, particularly where a considerable number of filters are to be added, it may be necessary to resort to other means of improving the transmission on the voice-frequency circuit, such as loading of incidental cables or the addition of a voice-frequency repeater.

On circuits equipped with way stations, selective signaling by means of selectors is sometimes used. Such signaling systems are generally arranged to apply an "answer back" tone to the line when a station has been called to indicate to the calling party that the selector has operated. This tone contains a considerable amount of high-frequency currents so that it is necessary to modify the selector circuit to filter out the high frequencies. The modification is a simple one and makes the answer back tone inaudible on the carrier circuit.

Design Features

In the development of the type-*H* system advantage was taken of many new devices which have been perfected in recent years, adapting them to the particular conditions of this application. A discussion of the more interesting features relating to the design of the various parts of the system is given below.

MODULATORS

The modulator and demodulator used in the type-*H* system are of the double-balanced copper-oxide type. Each modulator or demodulator consists of an input transformer, an output transformer, a copper-oxide "varistor" and a carrier supply. Although the modulators are bilateral, in the present application they are used in one direction only. The varistor consists of 48 copper-oxide disks assembled on a single bolt and connected as shown in figure 13.

The principal advantage of this type of modulator or demodulator is that in the ideal case (and to a lesser degree in the practical case) each modulation product appears only in one of the four branches of the circuit. For example in the case of the modulator, if a voltage of frequency V is applied to the input and a voltage of frequency C is applied by the carrier supply circuit, resulting products of modulation will appear in the ideal case as shown in figure 13. It is obvious that the only unwanted products in the output which cannot be suppressed by filters or balance are those which are of the frequency $(C \pm AV)$ which for some values of A and V fall in the frequency range of the desired sideband $(C + V)$ or $(C - V)$.

These components, however, are normally more than 50 decibels weaker than the sideband and are not noticeable. Of course, the term AV represents not only odd harmonics of V but odd order intermodulation products such as $(2V_1 \pm V_2)$. The relative amplitudes of the $(C \pm AV)$ terms increase with load in a similar manner to that for the distortion products of an amplifier as the overload point is approached, and the effect on articulation is the same.

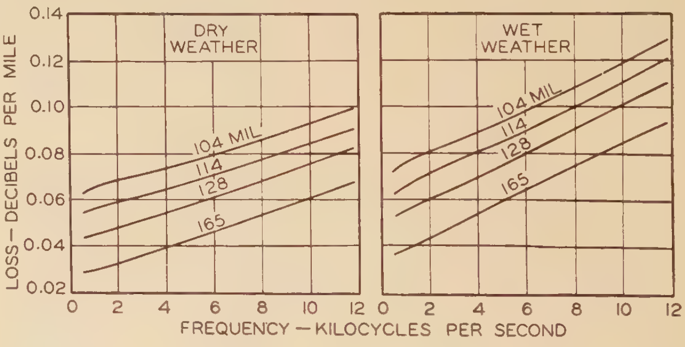

Figure 10. Attenuation of open-wire side circuits; 12-inch spaced copper wire with double-petticoat glass insulators

For the actual case the modulator balance is not perfect and all products and the original frequencies do appear in all branches of the circuit including the output. However, the balance in most cases is greater than 30 decibels and the filter requirements are helped to that extent over some portions of the frequency range. This is particularly helpful in connection with suppressing the carrier from the output and input since it lies only about 200 cycles from the pass band and it would be costly to obtain all of the suppression required by means of filters.

With a single disk in each arm, taking the factory run of disks and making no attempt to select units the balance for many assemblies would be less than 15 decibels. By selecting units, this balance could be improved to any desired amount. In the present design, however, to save the cost of selection 12 disks were used per arm to obtain the better balance resulting from the averaging of the characteristics of a large number of disks. There is some sacrifice in efficiency due to using the large number of disks but in this application it was of minor importance.

The averaging obtained by using 12 disks in each arm is helpful in several other respects. First, the normal impedance, transmission, and balance do not vary greatly from unit to unit. Secondly, although each disk has a negative coefficient of resistance vs. temperature and there is a variation in the coefficient among disks, the average coefficient of 12 disks chosen at random will be very nearly equal to the average of any other 12 disks chosen at ramdom and the balance between arms will, therefore, remain practically constant with temperature, even though the impedance and efficiency vary. A similar advantage is obtained in the case of aging and a good balance is obtained throughout the life of the equipment.

Oscillator

As mentioned previously the same carrier (suppressed) frequency is used for transmission in both directions, thus requiring a single oscillator instead of two as in the type-*D* system. The principal requirement for an oscillator for this use is that its frequency remain stable under the variations in power supply voltage and temperature which will occur. The new design which is shown schematically in figure 14, provides a degree of stability such that no operating adjustments will be required due to these factors. Relatively high stability with changes in temperature is obtained by balancing the positive capacitance-temperature coefficient of the copper-oxide load and the mica tuning condenser against the negative coefficient of the paper tuning condenser.

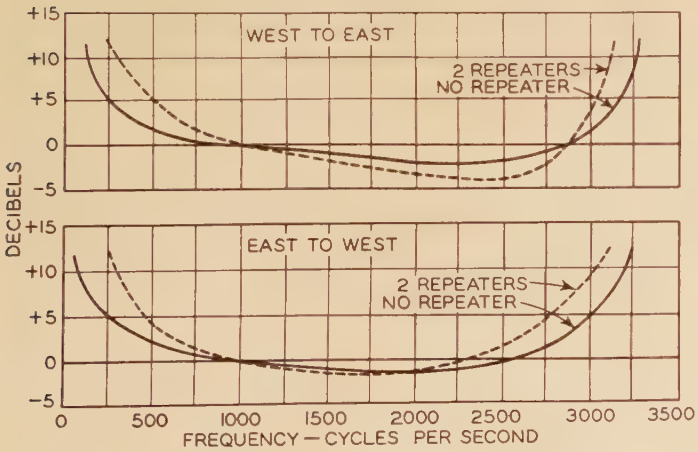

Figure 11. Representative over-all circuit net loss characteristic of system

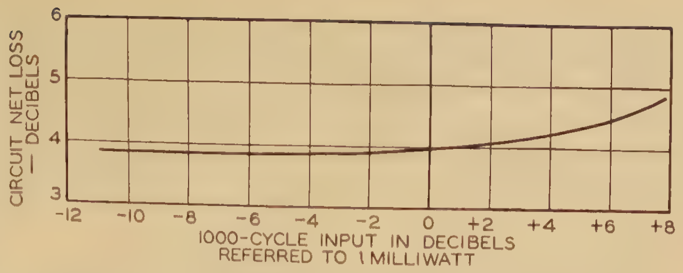

Figure 12. Representative system load characteristic

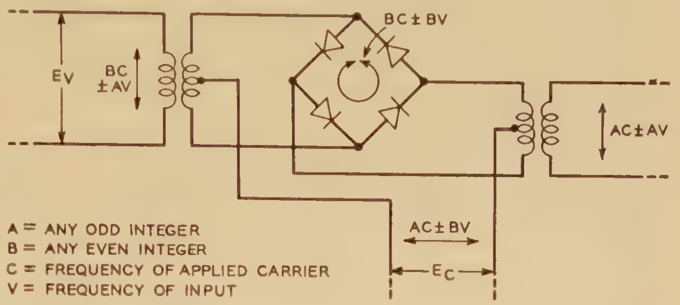

Figure 13. Simplified schematic of copper-oxide modulator

The stability of frequency with plate voltage variations is about $5/10^6$ parts per volt. This is adequate and was obtained without the use of an expensive tuning inductance. The coil used, which also serves as output and feedback transformer has a ratio of reactance to resistance of about 20 and is an air-core solenoid potted in a copper can.

Amplifiers

Both the receiving and transmitting amplifiers employ a single pentode with about 9 decibels feedback. For this amount of feedback, the variations of gain and impedance due to power supply variations are reduced to at least one-third of the amount of the variation obtained without feedback, and the load carrying capacity is increased about one decibel.

The two amplifiers differ in that the frequency range transmitted is different and in that the output transformer of the receiving amplifier also acts as an inequality ratio hybrid coil to separate the receiving signaling circuit from the two-wire voice circuit. The two circuits are shown in figure 4. In each case, the feedback is accomplished by means of a bridge circuit in the output and a series connection in the input. This can be more readily seen from figure 15, which is a simplified circuit representing both amplifiers. There is a considerable saving in circuit elements as compared to the familiar resistance bridge feedback connection. The output power loss due to shunt arms of the resistance bridge is eliminated. Furthermore, the impedance of the feedback circuit is relatively low, and consequently some wiring difficulties were avoided. In this application, the bridge is unbalanced, and the impedance Z_0 is a function of KR_0. As a result, it was convenient to adjust Z_0 to the optimum value by choosing the proper value of KR_0.

FILTERS

Filters constitute an important part of the type-*H* carrier system. They represent about 30 per cent of the cost of the terminal and occupy about 25 per cent of the total space.

The various filters required at a terminal are indicated in figure 16. The transmission characteristic of each filter is given in miniature above or below the block representing the filter.

The high-pass and low-pass line filters separate the ordinary voice telephone channel and the added carrier telephone channel made available by this system. The low-pass line filter passes voice frequencies and suppresses all other frequencies. The high-pass line filter passes the carrier frequencies and suppresses the voice frequencies. Each filter offers a high impedance to the frequencies passed by the other, and bridges off only a very small part of the energy of these frequencies.

The remaining filters are associated with the carrier terminal proper, where they serve to separate the transmitting and receiving paths and suppress unwanted frequencies. The voice frequencies pass through the hybrid coil and the transmitting low pass filter to the modulator. This filter limits the path between the hybrid coil and the modulator to voice frequencies only. Modulation of the voice with the carrier frequency of 7.15 kilocycles produces two sidebands extending from 4.15 to 6.90 kilocycles and from 7.40 to 10.15 kilocycles. At an east terminal, the upper sideband is transmitted, and the modulator output filter passes this sideband and suppresses the lower sideband, together with other unwanted modulation products. In this manner it limits the load on the amplifier to the desired sideband. The transmitting directional filter offers further suppression to frequencies lying outside this band. The receiving directional filter will not pass this band but has a high impedance to these frequencies. The high-pass line filter passes all frequencies above roughly 3.5 kilocycles and, therefore, this band passes through it readily and out onto the line for transmission to the distant terminal. Transmission from a west terminal is identical in principle but here the lower sideband is passed by the modulator output filter and transmitting directional filter while the upper sideband is suppressed.

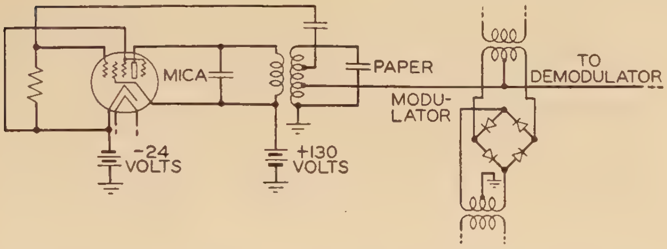

Figure 14. Schematic diagram of oscillator circuit

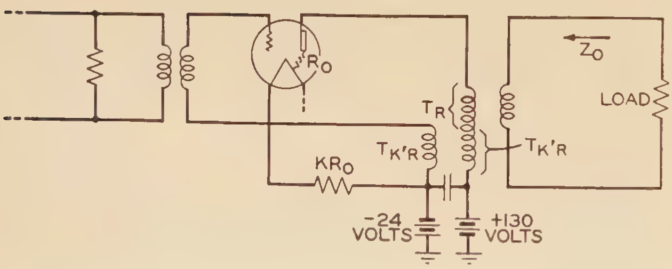

Figure 15. Simplified schematic of amplifier

It is apparent from figure 16 that the received sideband coming in on the line from the distant repeater or terminal is operated upon by the filters in a reverse manner from that described above for the transmitted sideband. The incoming frequencies are directed through the receiving directional filter to the demodulator, where modulation with the original carrier reproduces the voice frequencies together with other modulation products. The desired voice-frequency band is then separated from these products by the receiving low-pass filter.

In addition to performing the function of selecting desired and rejecting undesired currents, a filter, if operating in parallel with another as in the case of the directional filters or the line filters, should offer a high impedance to the transmitted currents of the other and thus prevent an excessive drain of these currents. Since these filters are designed for operation in parallel, either filter operated without the other would have somewhat different electrical characteristics.

The economies and reduction in size of these filters as compared to those of the type-*D* system are due to several factors. Improved paper condensers having the required stability are used. Compared to mica condensers, these condensers are less costly and smaller for a given capacity. Moreover, at a very slight increase in cost paper condensers are used which will withstand 1,000-volt line surges. Most of the condensers of the type-*D* system were designed for only 500-volt protection.

New types of coils with molybdenum permalloy cores having the necessary stability and low hysteresis losses are employed instead of the air-core solenoidal coils used in the type-*D* system. Since these new coils have less dissipation, the filters have flatter and wider transmission bands which contribute to improve telephone quality in the system. These coils are toroidal in shape and have very small stray fields and therefore small coupling with any nearby coils. This permits them to be packed closely together which results in a large decrease in the size of the filters. A further reduction in size and cost of the filters was effected by dispensing with individual containers for each coil. The elements of the filter are wired together and held in place in the filter can by a potting compound. This is poured around them, hermetically sealing the whole assembly.

The small size of the elements and the very low coupling

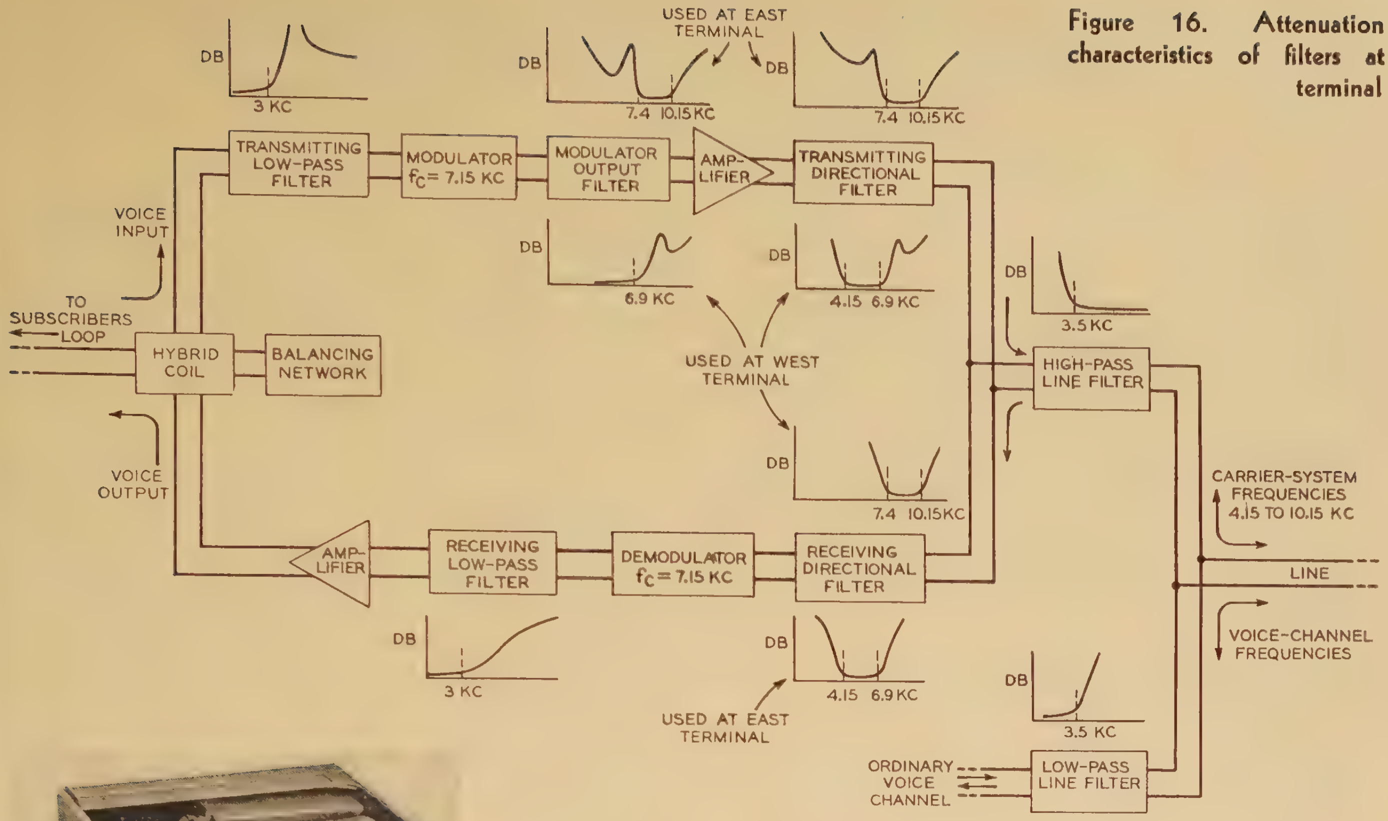

Figure 16. Attenuation characteristics of filters at terminal

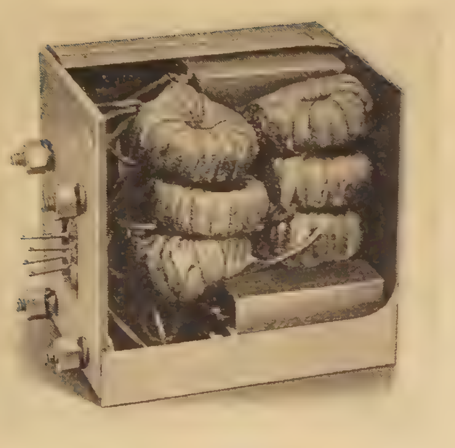

Figure 17. Filter (with cover cut away) showing general method of assembly

between them permit the assembly of more than one filter in the same can. For example, by a careful placing of the elements it was possible to place the transmitting and receiving low-pass filters and the modulator output filter in one can approximately three and one-fourth inches by four and one-fourth inches by four and one-fourth inches in size. A photograph of a high- and low-pass line filter with the can cut away is shown in figure 17. The filters for a terminal of this system require 70 square inches of mounting space or about one-fifth of that required for those of a type-*D* system.

Conclusions

The development of the type-*H* system is another step in extending the use of carrier systems. Improvements in performance and simplifications which are effective in reducing its cost as compared with the type-*D* system which it supersedes have been obtained. Reduction in size and provision for operation on a-c supply simplify its installation, particularly in outlying offices where suitable d-c power supply is not ordinarily available. Its portability makes it well suited to providing additional circuits required in cases of emergency. The type-*H* system is expected to have a large application in the Bell System telephone plant, and in addition to provide carrier circuits for the communication systems of other companies.

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Corona Voltages of Typical Transformer Insulations Under Oil

By F. J. VOGEL
ASSOCIATE AIEE

General

IN RECENT years, the importance of designing oil-immersed transformers to avoid deterioration during insulation tests has been emphasized. This is indeed proper, since it is very desirable to prevent deterioration in any form, especially when it may result in future trouble to the user. It has been found that insulation deterioration is caused by corona or local discharges in the oil and over solid insulation surfaces. It is therefore necessary that the designer know the laws of corona in oil, as determined by the configuration of the parts and the strength of materials.

In order to obtain these data, many tests have been made on barriers and models under oil, both with 60-cycle and impulse voltages.

The results of these tests show that, for essentially square-cornered parts, as in transformer constructions with interleaved insulation of the usual type, the dielectric strength varies approximately as the barrier thickness to the two-thirds power. These tests show that the ratio of impulse-voltage corona to 60-cycle corona is in the order of 2.2.[1,2] They also show that entrapped air within the insulation structure may greatly reduce the dielectric strength, and that the use of vacuum is very helpful in avoiding this difficulty.

In obtaining the data, two series of tests were made and a description of the test specimens, procedure and data follow.

Description of Barriers—First Series of Tests

The barriers tested were of three thicknesses, two and one-eighth inch, four and one-eighth inch, and seven inches. In order to simulate conditions in a transformer, an additional one-quarter-inch duct was placed between the barriers and the upper electrodes, making total separations of two and three-eighths, four and three-eighths, and seven and one-quarter inches. The barriers were all constructed with fullerboard sheets and ducts, similar to figure 1. Angles were interleaved as shown. The bottom electrode was a large plate. The top electrode consisted of five dummy coils of the same dimensions. The five coils were used in order to more closely simulate actual conditions in a transformer.

Each dummy coil was made of a three-eighths-inch-thick fullerboard sheet covered with lead foil, taped, and varnished, to a total thickness of about one-half inch. These coils were assembled with five-sixteenths-inch spacers between coils. The spacing between the coils and the angles was varied, the intervals being three-eighths, three-quarters, one and one-half, and three inches.

Test Procedure—60 Cycles

These tests were made to determine the voltage required to break down the oil between the upper electrode and the first angle. The barriers were tested under oil at 70 degrees centigrade, and special precautions were taken to eliminate any corona on the leads both under the oil and in the air. Audible corona was noted both by the use of a microphone under the oil, and by observers placing their ears directly against the tank.

The actual procedure during the tests is best described by giving, step by step, the results of the tests on a four and one-eighth-inch-thick barrier, with the dummy coils three inches from the first angle. After the barrier was immersed in the oil, it was shaken and the upper electrodes pounded. Considerable air was removed by this process. Then 125 kv was applied. Corona, which was present as shown by intermittent clicks, stopped abruptly after three minutes. When the voltage was removed, some air and gas escaped. Next 150 kv was applied and corona again appeared, gradually becoming weaker and at longer intervals, say 30 or 40 cycles, and disappearing. The voltage was removed, and the barrier shaken, and more bubbles were driven out. Then 180 kv was applied for five minutes, with no corona appearing during the last four minutes. At 200 kv, deterioration set in as indicated by a weak steady buzz. The voltage was immediately removed and then 150 kv, 180 kv, and 195 kv were applied without a sign of corona. Above 200 kv, corona appeared regularly, and thus 200 kv was determined as the corona voltage for this arrangement.

In every case, when bubbles were present, it was found that either the air had not all been removed, or that there

Table I. Test Results—60 Cycles—Oil Temperature Approximately 70 Degrees Centigrade

Barrier Number	Separation Dummy Coils to Plate	Distance Dummy Coils to Angle	Corona Point-Kv RMS	Maximum One-Minute Hold
1	$2^{3}/_{8}$	$^{3}/_{8}$	180	225
2	$2^{3}/_{8}$	$^{3}/_{4}$	170	240
3	$2^{3}/_{8}$	$1^{1}/_{2}$	150	250
4	$2^{3}/_{8}$	3	130	
8	$4^{3}/_{8}$	$^{3}/_{8}$	290	360
9	$4^{3}/_{8}$	$^{3}/_{4}$	280	
10	$4^{3}/_{8}$	$1^{1}/_{2}$	260	350
16	$4^{3}/_{8}$	3	200	
18	$7^{1}/_{4}$	$^{3}/_{4}$	360	466

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[1] For all numbered references, see list at end of paper.

was corona and insulation deterioration. In the determination of the corona point, it was required that a slightly lower voltage be held for five minutes without either bubbles or audible disturbance.

Procedure—Impulse Tests

Two series of tests were made, all using approximately $1^1/_2$x40 positive full waves. One series was made to failure, by applying at least 100 surges at each voltage setting. Another series was made by removing the barrier from the oil after 100 surges at each voltage setting, and determining the voltage at which marking was observed. The air was removed as far as possible by shaking the barriers.

Discussion of Results—First Series of Tests

These results are of importance because they show how entrapped air affects the insulation strength of an assembly under oil. They are also of importance in showing how the strength of oil is affected by the distance between the electrode and the barriers. Some of the values given by table I are shown on figure 2. This figure indicates that for a given arrangement the breakdown or corona voltage varies as the two-thirds power of the separation between the dummy coils and plate. The values also indicate that neither the 60-cycle nor impulse breakdown are much affected by the distance *B* between the coils and the first barrier for these particular tests, but this is not necessarily true in general, as shown by later tests. Table II also shows that insulation may stand hundreds of surges above the corona voltage as established by insulation marking. They also show that the impulse ratio for corona voltages is in the order of 2.1, but later tests on samples more closely similar to actual transformer construction, show a ratio of 2.2 or over.

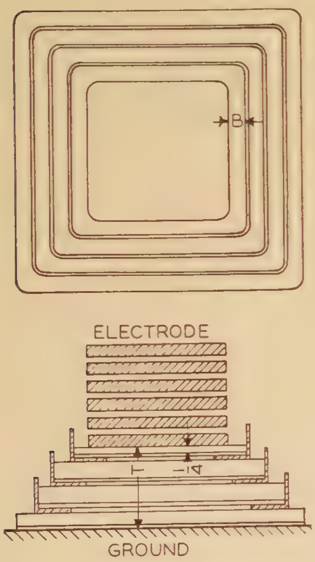

Figure 1. Sketch showing typical arrangement of barriers in the tests. B was three-eighths, three-quarters, one and one-half, and three inches. T was two and three-eighths, four and three-eighths, and seven and one-quarter inches

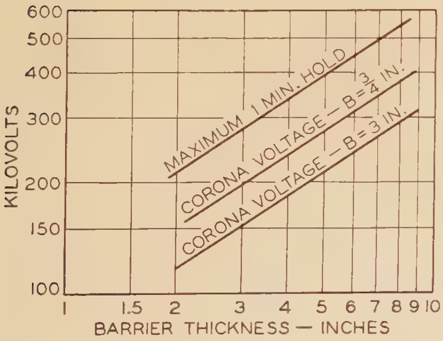

Figure 2. Relations between maximum one-minute hold or corona voltage and barrier thickness. Data taken under oil at approximately 70 degrees centigrade and with 60-cycle voltages

Table II. Breakdown Test Results—Impulse Tests—Oil Temperature 76 Degrees Centigrade

Barrier Number	Separation Dummy Coils to Plate	Distance Electrode to First Angle	Voltage in Kv	Number of Surges and Remarks
1	$4^3/_8$	$^3/_8$	870	100
			920	Failed on 59th Surge
2	$4^3/_8$	$^3/_8$	870	260—Slightly marked
			920	Failed on 187th Surge
3	$4^3/_8$	$^3/_8$	870	230
			920	Failed on 80th Surge
4	$4^3/_8$	$^3/_8$	870	Failed on 240th Surge
5	$4^3/_8$	$^3/_4$	820	446
			870	Failed on 161st Surge
6	$4^3/_8$	$^3/_4$	870	293
			920	Failed on 136th Surge

Table III. Endurance—Corona-Voltage Tests

Barrier Number	Separation Dummy Coils to Plate	Distance Electrode to First Angle	Voltage in Kv	Number of Surges and Remarks
12	$4^3/_8$	$^3/_8$	790	100—No marks
			830	100—Marked
7	$4^3/_8$	$^3/_4$	720	100—No marks
			790	110—No marks
			850	110—Marked
8	$4^3/_8$	$^3/_4$	790	100—No marks
			820	100—Marked
10	$4^3/_8$	3	590	100—No marks
			620	100—Marked
11	$4^3/_8$	3	590	100—No marks
			620	100—Marked

Table IV. Comparison of Corona Values—60 Cycle and Impulse

Separation Dummy Coils to Plate	Distance Electrode to First Angle (Inches)	Corona Voltage		Ratio Impulse to 60 Cycles
		60 Cycle Crest-Kv	Impulse Kv $1^1/_2$ x 40 Pos. Wave	
$4^3/_8$	$^3/_8$	410	830	2.0
$4^3/_8$	$^3/_4$	396	835	2.1
$4^3/_8$	3	282	620	2.14

Description of Barriers—Second Series of Tests

Since the preceding tests confirmed the necessity of removing all air, it was decided to make another series of tests, impregnating and filling the models with oil under vacuum. The insulation around the coil conductor has considerable bearing upon the dielectric strength, and so the new models were made with dummy coils of copper ribbon taped to 0.120 inch thickness with paper. The distance from the insulated coil to the first angle was from three-eighths to three-quarters inch. The barrier thickness was two and five-eighths inches.

Test Procedure—60 Cycles and Impulse

In these tests, the voltage was raised in steps, holding the voltage for one minute at each step, until corona appeared as indicated by the formation of fine bubbles. A similar procedure was followed in obtaining impulse data, except that 100 positive wave impulses were applied at each voltage step. The impulse voltages were chopped by a gap at approximately three microseconds.

Table V. Results of Second Series of Tests

60-Cycle Corona	Impulse Corona
285	917
281	920
Average—283	918

The impulse ratio—impulse voltage at approximately 3 microseconds to 60 cycle crest voltage—is approximately 2.29. Corona at 60 cycles was not indicated until the breakdown voltage was reached.

Discussion of Results—Second Series of Tests

The results of these tests show how effectual the application of vacuum is in obtaining the full insulation strength of a transformer without the necessity or risk of carefully building the voltage up, and making so-called "bubble runs." They show clearly that large high-voltage transformers will have their maximum dielectric strength immediately when put in service, if filled with oil under vacuum. It also shows that the ratio of impulse to 60-cycle corona is of the same order as the impulse ratio of breakdown previously given, namely, 2.2 or more.

Conclusions

1. These tests, and previous experiences with models of transformers, show that corona can be avoided in transformers, both for 60 cycles and for impulses. It also shows that an average ratio between the impulse and 60-cycle crest voltage corona point of insulation similar to actual transformer insulation is 2.2.

2. These tests show the importance, both from a 60-cycle and impulse viewpoint, of the removal of all entrapped air. It is shown to be desirable to fill transformers with oil under vacuum, both for factory tests and at the time of installation. Tanks for many transformers of the larger sizes and higher voltages are made suitable for the application of vacuum.

3. These tests show that in some cases insulation will stand hundreds of impulses slightly above the corona point. This situation is similar to that found in 60-cycle tests, in which insulation withstands a higher value for one minute than the "marking" value.

Acknowledgment

The data covered in this paper were obtained over a period of years, and to those who helped in obtaining it, especially Mr. Carl Alsing and Mr. W. L. Teague, acknowledgment is due.

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Recent Advances in Resistance Welding

DURING the past few years fundamental concepts of resistance welding have not been greatly changed, progress being limited mostly to refinements in the art of welding procedure, design of machines and auxiliary equipment, and broader applications to industry in general. Advances may be classified under the headings of time, pressure, and current control which are fundamental to all resistance welders, materials to be welded including their preparation for welding, and means for placing the parts in the welding machine.

Perhaps the most noteworthy improvements have to do with the accuracy of the time period of current application. Controls whereby the primary current of the welding transformer is fed directly through either thyratron or ignitron tubes are coming into general use since they make practicable perfect timing of current application in exact periods of one-half cycle or larger multiples thereof. The maximum root mean square current capacity of these tubes has also been steadily increased up to 10,000 amperes at present for continuous welding operations. Not only have these exact tube controls been developed for use with much higher currents than were formerly used, but at the same time they have also made possible satisfactory commercial welding of materials which can only be welded in these short time intervals at high current densities. An auxiliary development to purely electronic timing is heat control which is accomplished by suitably delaying the ignition point of each tube for each half cycle of power current conducted and consequently cutting down the weld power for each half cycle. This has been used as a substitute, but usually as an auxiliary to the tap switch on the welding transformer for critical welding heat adjustments.

Probably stimulated by the performance of electronic control, very marked improvements in the operating speed of spot welding contactors has taken place. Also a large number of devices have been developed for more accurately controlling these contactors. Sending a current pulse of very brief duration or a series of impulses to the contactor magnet coil as determined by the rate of charge or discharge of a condenser, the inductance of a coil, or the operation of sensitive relays controlled by clock motors has allowed more satisfactory operation of magnetic contactors while refinements in the operation of mechanical contactors as synchronously co-ordinated with the welding circuits has also been considerable. Air-operated weld timers are also proving quite satisfactory on some classes of work and multiple control units are being used on automatic spot welders for controlling contactors and the motion of air operated heads and their dwell.

Welding machines have undergone marked improvement in the last few years, and this improvement is undoubtedly partly due to the more precise control now available. Pressure means on press welders such as air-cushion chambers in combination with cam action and the elimination of pounding are decided steps forward. The use of initial and final pressures on projection welding is also quite common. Better synchronization of machine operation and control makes possible fully automatic spot and projection welders with semiautomatic feed and discharge of parts to and from the welding position. Flash welders afford much better flash protection and the jaw movements whether co-ordinated by cam, spring, air, or hydraulic action or combination thereof have been much improved. Much higher capacities of transformer are being used and kilovolt-ampere capacities considerably over 1,000 are not at all unusual. Means for adjusting the welding current in smaller steps are more often provided especially for nonferrous materials. Some machines are also equipped with milling cutters which machine the work piece at their contact points prior to welding which reduces the possibility of variable power input into the weld area in successive welding operations. The use of automatically operated resistance welders for accurate annealing temperatures as controlled by photoelectric cells focused on individual parts has reached a high degree of development.

Multitransformer and multielectrode machines have come into extensive use during the last three years. Multielectrode machines such as the hydromatic spot welder using either one or more transformers has made possible very rapid spot welding on large assemblies and in addition has made possible individual quality control for each weld. Multitransformer machines are used to insure quality in individual weld spots and also to insure the proper current distribution on projection welding platens or large flash welding machines.

In order to speed up spot welding operations on strip materials wheel type electrodes are used under conditions similar to seam welding, but with longer periods of current interruption and consequent speeds as high as 120 feet per minute.

Special machines such as portable spot welders used for large assemblies of sheet iron parts and light frameworks are more popular than ever and are finding many more applications outside of the automobile industry where they were first put to use. In order to reduce the weight of the gun and lessen operator fatigue on large portable welders these are being built of aluminum or magnesium alloys in the hydromatic type so that the pressure cylinder is only about one inch in diameter instead of four or five. Plier type welders which are really miniature portable spot welders are also used for making electrical connections on meters, radios, or similar apparatus. Even percussion welders of which there are relatively few are increasing in number and the discharge of a bank of con-

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A report of the subcommittee on resistance welding of the AIEE committee on electric welding, scheduled for presentation at the winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted October 19, 1937; released for publication October 28, 1937.

Personnel of the subcommittee on resistance welding of the AIEE committee on electric welding: C. L. Pfeiffer, *chairman;* Malcolm Thomson, Carroll Stansbury, C. E. Heitman, J. W. Dawson, F. E. Taylor, H. A. Woofter, R. L. Browne, H. E. Stoddard, and Herman Lemp.

densers or its equivalent into the primary of a resistance welding transformer finds applications on very critical welding setups.

Interrupted spot welding sometimes known as "persistence" welding is a relatively new method of welding very heavy sheets up to one inch in thickness. A series of welding current impulses is sent through the electrodes of a conventional spot welding setup giving the weld area time to heat up at the point of fusion but allowing the surface in contact with the electrodes to remain relatively cool. Such a set-up operates most consistently and with the best results by using electronically and automatically controlled timing periods, water-cooled electrodes and materials which spot weld readily such as low-carbon steel.

Practically all users of resistance welding machines now use either die-type electrodes or electrode tips made of special electrode materials. The use of these materials in die-type electrodes in combination with satisfactory cooling media makes possible the extension of resistance welding to a wide variety of special shapes including many not of sheet form. In addition to the tungsten-copper combinations and the cadmium copper alloy there are now a number of other electrode alloys available such as silver-tungsten and those which consist principally of copper, but contain small percentages of chromium, molybdenum, cobalt, beryllium, silicon, or zirconium.

The industries in which the application of resistance welding has made considerable strides and are using more welding equipment are radio, aircraft, electric machinery and equipment, refrigeration, metal sash and window frame, automobile, metal wares, telephone, farm machinery, railroad equipment, and metal furniture.

In the past, frequent criticism has been heard because many users of and even some manufacturers of resistance welding apparatus have operated on a decidedly rule-of-thumb basis. Attempts are being made to put resistance welding on something approaching a quantitative, scientific basis and some progress has been made by the introduction of various simple meters and measuring devices, especially adapted to the peculiar requirements, such as means for measuring the time of current application, electrode pressure meters, and instantaneous type current meters employing a gaseous glow lamp as the measuring element. Some tables have also been published showing the proper electrode area, time, current, and pressure to use on specific material of given dimensions. It is also felt that more effort should be expended on standardization of transformer and secondary circuit performance of welding machines and that more coordination along these lines between manufacturers of this equipment is desirable.

Temperature Limits for Short-Time Overloads for Oil-Insulated Neutral Grounding Reactors and Transformers

By V. M. MONTSINGER
FELLOW AIEE

THE PROTECTIVE DEVICE committee is working on the problem of preparing standards for neutral grounding devices. One of the most important points up for consideration is the selection of the temperature limits for various times of operations of the devices.

At the present time grounding transformers are designed to withstand a one-minute short circuit (duration of fault) without exceeding a temperature of 160 degrees centigrade.

The increasing use of oil-immersed neutral grounding devices—reactors, transformers, and Petersen coils—where the fault may last several minutes makes it necessary to standardize safe temperature limits for the longer periods of time.

In the case of grounding transformers the 160-degree-centigrade temperature limit is based on all heat being stored in the copper (neglecting the insulation) during the one-minute period. Obviously, where the time of fault lasts several minutes the maximum temperature reached will be influenced considerably by some loss of heat during the heating up period, especially if the winding has oil ducts between all coils. In other words, both heat storage and dissipation should be taken into consideration.

On the other hand, since many neutral grounding devices carry no load except during the fault, windings with no oil ducts between coils can and are sometimes used. In this case very little loss of heat will take place in the interior of the coil stack during the heating up period and the maximum temperature can be based on all heat being stored in the copper and its insulation. Again in this case the rate of cooling after the fault is removed is very much less than it is for coils with oil ducts. In fact, as shown later the cooling period of coils with no oil ducts is the controlling factor so far as aging of the insulation is concerned. Coils with oil ducts will be termed "open type" coils and coils with no oil ducts will be termed "closed type" coils.

It is the purpose of this paper to calculate the temperatures for various lengths of faults—up to 30 minutes—that will produce the same aging of insulation as is produced by 160 degrees centigrade for a period of one-minute fault—the present standard for grounding transformers.

I. Aging of Insulation

It is obvious that short-time temperature limits should be based upon the aging of the insulation. By aging is meant the mechanical deterioration (tensile strength) since electrical deterioration does not take place[1] until the material has become quite brittle and well carbonized.

To estimate the relative aging of insulations under short-time overload conditions, three steps must be taken, namely:

1. Calculation of the temperature rise of the winding until the load is removed.
2. Calculation of the cooling of the windings after the load is removed.
3. Integration of the area represented by the heating curve, taking into account both temperature and time.

Two types of coils are considered. First, coils of open type construction. Second, coils of closed type construction.

II. Heating Curve of Open Type Coils

Figure 1 shows a typical heating curve until conditions become constant of an oil-immersed transformer winding. This curve was based on the average of three curves having final copper rises in excess of the oil of 27, 42.5, and 86 degrees centigrade given on figure 5 of a previous AIEE paper.[2]

III. Cooling Curves of Open Type Coils

The cooling of windings of the open type construction has been calculated by an empirical formula shown later since, as was pointed out, in the AIEE paper,[3] the standard cooling curve equation $\theta_t = \theta_0 e^{-\beta t}$ does not apply to the usual open type oil-immersed winding. The cooling curves in terms of watts per pound, figure 2, were based on the formula (equation 8, reference 3):

$$\theta = 1.95\, W_c^{0.7} (1 - e^{-Lt}) \tag{1}$$

where

θ = cooling in degrees centigrade
W_c = watts per pound of bare copper
= $2.16 \times 10^{-6} D^2$ (at 25 degrees centigrade) where D = amperes/square inch
e = 2.718
L = $0.106\, W_c^{0.3}$
t = time in minutes

To use the cooling curves shown in figure 2 under transient heating conditions (i. e., before the rise becomes constant) the temperature rise at the instant load is removed must be obtained in terms of watts per pound of bare copper for constant conditions. In other words, the watts per pound that would give the temperature rise (at the instant load is removed) for constant conditions must be found. Such a curve is shown in figure 3 for a typical

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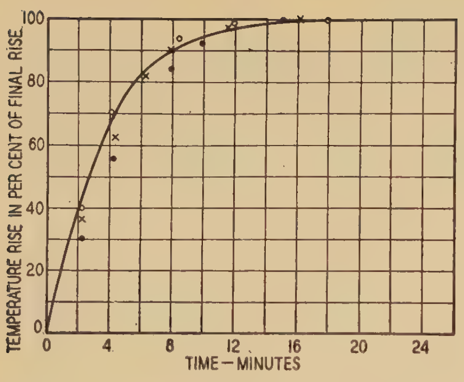
[1] For all numbered references, see list at end of paper.



Based on three curves (27 degrees, 42.5 degrees, and 86 degrees copper over oil- final rises) figure 5 of reference 2

Based on curve with:
- • 27-degree final rise
- × 42.5-degree final rise
- o 86-degree final rise

Figure 1. Temperature rise of horizontal disk coils. Copper rise over oil until conditions become constant

coil stack.* For example, if, when the load or fault is removed, the temperature rise (over oil) is 55 degrees, 100 watts per pound (W_c) should be used in calculating the cooling by equation 1.

IV. Relative Aging of Insulation for Various Overloads

Several years' experience with grounding transformers has indicated that 160 degrees centigrade for one minute is satisfactory. As a working base it is therefore assumed that 160 degrees centigrade is safe for a one-minute load. It has been shown[1] that the rate of aging doubles for each 8 degrees centigrade increase in temperature or conversely is halved for each 8-degree decrease in temperature, and that the general form of the equation for expressing aging (or relative aging) as a function of both time and temperature can be written:

$$A = t_0 e^{0.088 T_2} \tag{2}$$

where

A = units of aging
t_0 = time in minutes
e = 2.718
T_2 = temperature in degrees centigrade

In its present form equation 2 gives only relative aging units of insulation resulting from a continuous temperature T_2 applied for a length of time to, and represented by the rectangular area of the time-temperature graph. Later an empirical constant is added for the purpose of giving some idea of how long the insulation will last in service.

The equation for integrating temperature areas in the form of triangles and trapezoids is of the form

$$A = t_0 \left[\frac{e^{0.088 T_2} - e^{0.088 T_1}}{0.088 (T_2 - T_1)}\right] \tag{3}$$

where T_2 and T_1 are the maximum and initial temperatures respectively of a triangle, but for a trapezoid T_2 and T_1 represent the vertical parallel sides—t_0 being the base of both triangles and trapezoids. See figure 7. See appendix for derivation of equation 3 and examples worked out.

Figure 4 shows the temperature limits for various durations of overloads on open type coils starting at 25 degrees that give approximately the same degree of aging obtained where the temperature reaches 160 degrees centigrade at the end of one minute. Figures 5 and 6 show similar curves except that the starting temperature is 75 degrees centigrade.

The methods used in integrating the temperature curve areas are illustrated in the appendix.

The results of these calculations are shown in table I.

Table I. Relative Aging of Open Type Coils

	Initial Temp. 25 Deg.		Initial Temp. 75 Deg.	
Time of Overload (Minutes)	Maximum Temp. (Deg. Cent.)	Units of Aging	Maximum Temp. (Deg. Cent.)	Units of Aging
1	160	380,000	160	778,000
5	149	405,000	149	770,000
10	139	410,000	138	799,000
30	112	400,400	119	787,400

It will be seen from table I that the amount of aging where the starting temperature is 75 degrees is approximately double that where the starting temperature is 25 degrees centigrade. The reason for this may be explained as follows: with a lower initial (oil) temperature, a greater overload is required to reach a given temperature limit than is required with a higher initial (oil) temperature. The higher the overload (or losses), the steeper the heating-up curve will be. Also, the higher the rise (over oil) at the time overload is removed, the faster in degrees per minute will be the cooling. (It is assumed that the oil temperature does not materially change during the entire period of heating and cooling.)

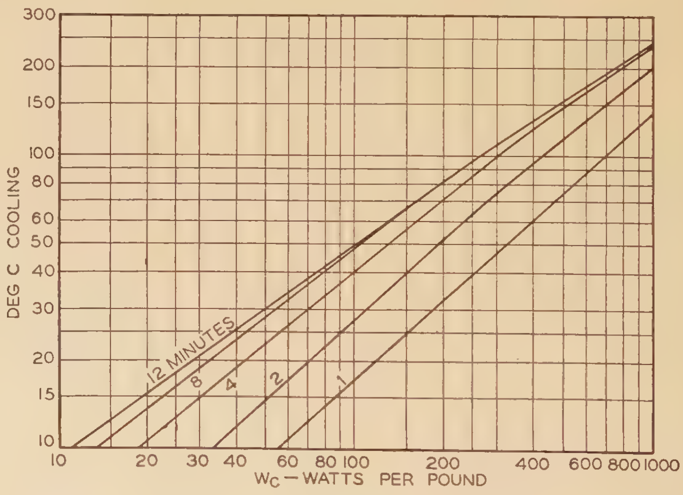


Figure 2. Cooling after shutdown of coils (with oil ducts)

Calculated by equation 1

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* This curve was determined by tests on typical coils. The equation of the curve is

$\theta = 1.38 W_c^{0.8}$

where θ is the temperature rise over average oil temperature and W_c is the watts per pound of bare copper. In all cases where temperature rise is mentioned, it means the copper rise in excess of the oil temperature.

The result is that with the steeper heating curves and faster cooling curves (with the lower initial temperature and greater overloads) the areas near the top of the heating and cooling curves are smaller than they are with the higher initial temperature and lower overloads. This difference in the areas can clearly be seen in the curves shown in figures 4 and 5. Since most of the aging occurs near the peak temperatures the size of the top areas is very important and hence the aging is less for the lower initial temperature. This means that to obtain the same aging during the overload period, for 25-degree initial temperature, approximately 8-degrees higher temperature could be allowed than for 75-degree initial temperature, since, it has been assumed that aging doubles for each 8-degree increase in temperature. In fact, the difference would be more than 8 degree because this does not take into account the aging during the time when no overloads are on, during which time it would, of course, be greater for a continuous temperature of 75 degrees than for a continuous temperature of 25 degrees centigrade.

Based upon the assumption that 160 degrees centigrade is safe for one minute and upon the values shown in table I, it would seem that the following temperature limits (or some of these limits) could be standardized for oil-immersed grounding neutral devices of open coil construction.

Table II. Temperature Limits for Open Type Coils

Overload Time (Minutes)	Degrees Centigrade
1	160.0
2	157.5
3	155.0
5	150.0
10	140.0
20	125.0
30	120.0

For closed type coil (with no oil ducts) the temperature limits, for a given initial temperature, are obviously lower than for open type coils for the reason that the cooling period is much longer than for open type coils. Based on the rate of aging being halved for each 8-degree decrease in temperature, to keep the aging on a coil stack with no oil ducts to the same value as for an open type coil reaching 160 degrees in one minute, the temperature should not exceed approximately 135 degrees centigrade. On the other hand, there is very little difference in aging whether the heating up period is one minute, five minutes or ten minutes, since most of the aging takes place after the load is removed.

Since most, if not all, neutral grounding devices of the Petersen coil type operate only when there is a fault and where the starting temperature would be at room temperature, it would seem that devices with closed type coils could operate during a fault at somewhat higher temperatures than could devices with open type coils, which permit of carrying some load continuously if occasion demands it. In other words, it may be safe to use the temperature limits given in table III for coils of the closed type. This is a question that should be given consideration when selecting temperature limits for standardization purposes.

HEATING AND COOLING OF CLOSED TYPE COILS (NO OIL DUCTS)

In calculating the time-temperature curves of the closed type coils the heating-up curves were taken as approximately straight lines (except for the slight increase in resistance with increasing temperatures) since there is very little, if any, dissipation of heat from the interior of the coil stack during the short periods of time under consideration. Also, both the temperature rises and cooling curves were based on the thermal capacity of both the copper and intervening insulations. The thermal capacity of oil-immersed fibrous insulations is, by volume, approximately one-half that of copper.[3]

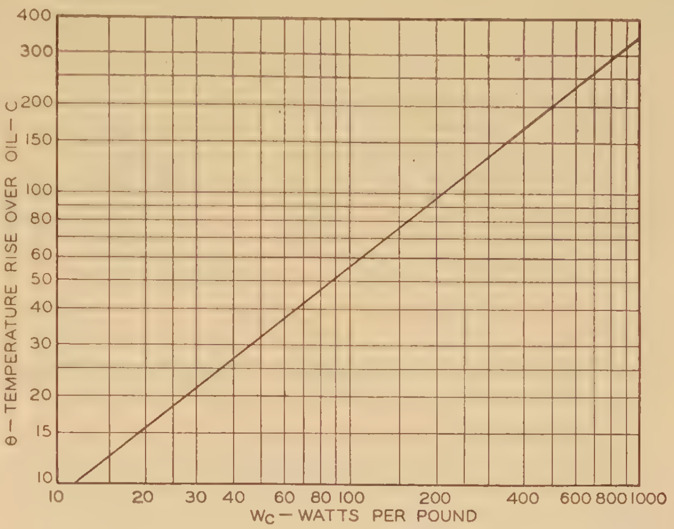

Figure 3. Temperature rise versus watts per pound of coil stack with oil ducts

Equation $\theta = 1.38\ W_c^{0.8}$

The cooling after load is removed was calculated by the standard cooling curve equation given in the first part of this paper. The size of conductor used in a closed type coil stack* on which tests were made to determine the curve of watts per pound versus temperature rise (for constant conditions) was 0.400 by 0.040 inch having 0.021-inch two sides thickness of insulation.

From the above

$$3 = \frac{W_c 0.676 \dfrac{a}{A + a}}{\theta_0}$$

$$= \frac{0.259\ W_c}{\theta_0}$$

where a = 0.400 by 0.040 inch
and A = 0.421 by 0.061 inch

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* Consisting of 19 coils with no oil ducts.

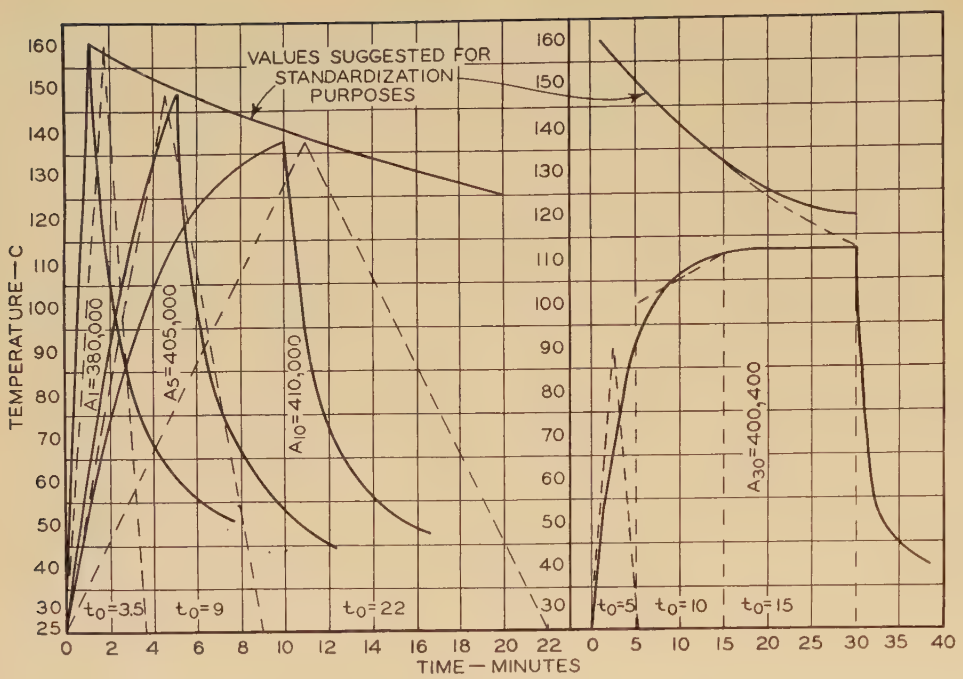

Figure 4. Various durations of loads and temperatures of oil-immersed windings (with coil ducts) to give approximately the same degree of aging of the insulation

Initial temperature T_1 = 25 degrees centigrade

Formulas shown in figures 5 and 6

The equation of winding rise for constant conditions was found by tests to be

$$\theta_0 = 18.25\ W_c^{0.64}$$

The cooling curve can easily be calculated by the general equation $\theta_t = \theta_0 e^{-\beta t}$.

The aging for a load attaining 160 degrees centigrade in one minute with a 25-degree initial temperature is approximately 3,290,000 units.

For a load attaining 152 degrees centigrade in 20 minutes the aging is approximately 3,000,000 units.

If it is assumed that 160 degrees is safe for one minute for closed type coils, calculations (for 25-degree initial temperatures) indicate that the following temperature limits could be permitted for 5, 10, 20, and 30 minutes.

Table III. Temperature Limits for Closed Type Coils

Overload Time (Minutes)	Degrees Centigrade
1	160
5	158
10	155
20	150
30	145

Since the aging in the above cases is in the order of 3,000,000 units, it is roughly 7.5 times that of an open type coil stack with 25-degree initial temperature.

It should be understood that the temperature limits obtained by the methods used in this paper are at best only approximations. Different designs will have different shapes of heating and cooling curves, although it is believed that the kind of coils chosen for these calculations are fairly well representative of the type of coils used. However, these calculated values should be more dependable than values arbitrarily chosen without any supporting data.

V. Life Expectancy

The life of any neutral grounding device obviously depends not only on the temperature limits chosen but also

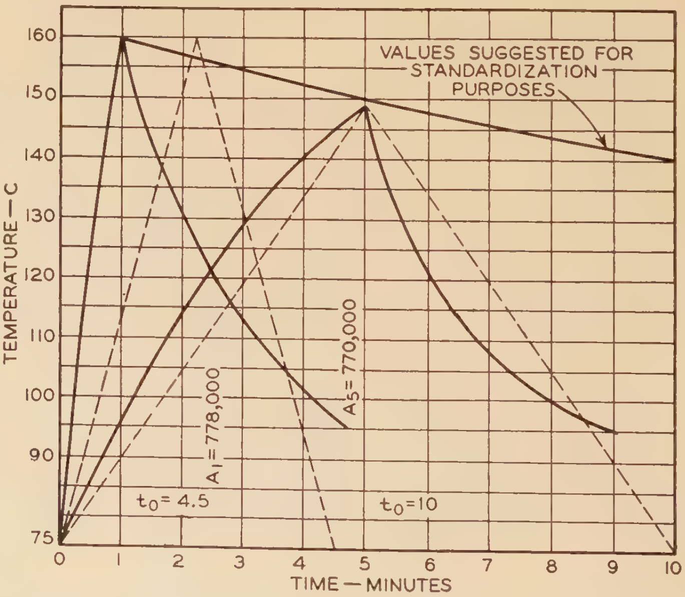

Figure 5. Various durations of loads and temperatures of oil-immersed windings (with coil ducts) to give approximately the same degree of aging of the insulation

Initial temperature T_1 = 75 degrees centigrade
T_2 = 160 and 149 degrees centigrade

$$A = t_0 \left[\frac{e^{0.088T_2}\ e^{0.088T_1}}{0.088\,(T_2 - T_1)}\right]$$

on the frequency of operation, which, of course, is unpredictable for this kind of service.

The following formula has been given[1] for estimating the life of insulation when operating continuously at various temperatures:

$$Y = 7.15 \times 10^4 e^{-0 \cdot 88x} \tag{4}$$

where

Y = life in years
x = temperature degrees centigrade
e = 2.718

Equation 4 gives the following years of life for 90, 95, 100, and 105 degrees centigrade temperatures:

Table IV

Temperature (Deg. C.)	Years—Life (Approximate)
90	26
95	17
100	11
105	7

If we choose 26 years as a reasonable life, this means that the equivalent of 90 degree continuous temperature should not be exceeded.

By equation 2 the units of aging for 26 years at 90 degrees is

$$A = (26 \times 365 \times 24 \times 60)\, e^{0 \cdot 088 \times 90}$$
$$= 37{,}600{,}000{,}000 \text{ units}$$

With an initial temperature of 25 degrees the number of permissible operations per day would be (approximately):

$$\frac{37{,}600{,}000{,}000}{26 \times 365 \times 395{,}000} = 10 \text{ times for open type coils,}$$

or,

$$\frac{37{,}600{,}000{,}000}{26 \times 365 \times 3{,}000{,}000} = 1.3 \text{ times for closed type coils.}$$

These numbers of operations appear to be more than would ever occur under service conditions.

Conclusions

As a result of the study given in the paper the following conclusions have been drawn:

1. These data should make it possible to establish fairly dependable temperature limits for short-time overloads for oil-immersed neutral grounding devices.

2. For neutral grounding devices having open type coil construction, where the time exceeds one minute, most of the aging of insulation takes place during the heating-up period.

3. For neutral grounding devices having closed type coil construction, most of the aging takes place after the overload is removed; that is, during the cooling period.

4. For neutral grounding devices that carry no load, except during a fault, the temperature limits given in table III should be safe for standardization purposes.

Appendix

Derivation of equation 3:

Let

A = aging units
T = temperature, degrees centigrade
T_2 = maximum temperature degrees centigrade
T_1 = some lower temperature—see figure 7
t_0 = time in minutes

When the aging doubles for each 8-degree increase in temperature, the exponential constant is 0.088. Therefore:

$$A = \int_0^{t_0} e^{0 \cdot 088T} dt$$

$$T = T_1 + (T_2 - T_1)\frac{t}{t_0}$$

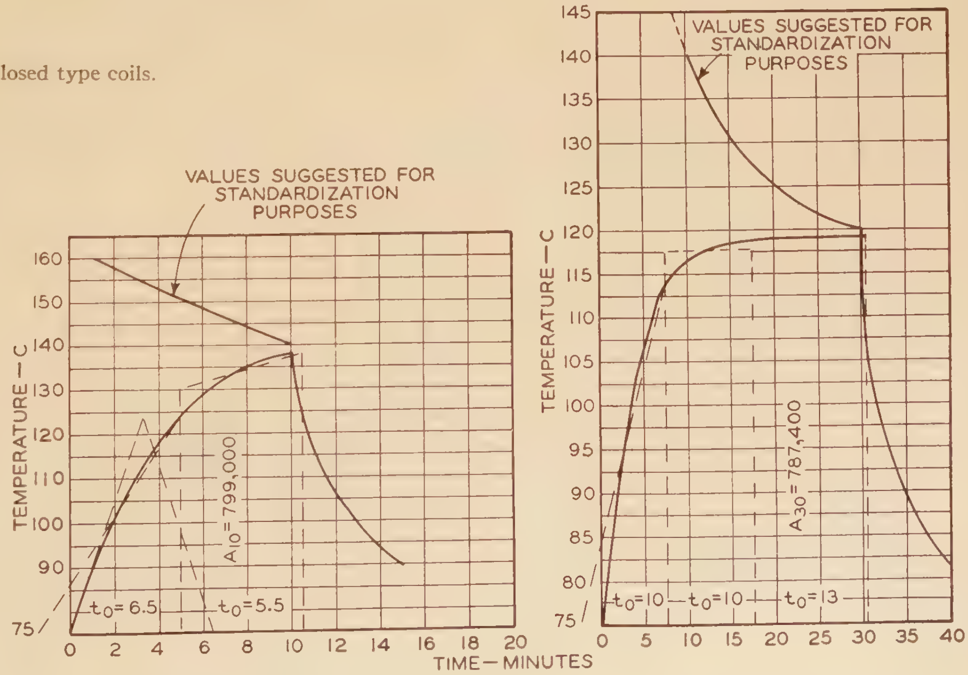

Figure 6. Various durations of loads and temperature of oil-immersed windings (with coil ducts) to give approximately the same degree of aging of the insulation

Initial temperature T_1 = 75 degrees centigrade

$A = t_0\, e^{0 \cdot 088T_2}$ (for rectangles)

Formula shown in figure 5 used for triangles (T_1 = 75 degrees)

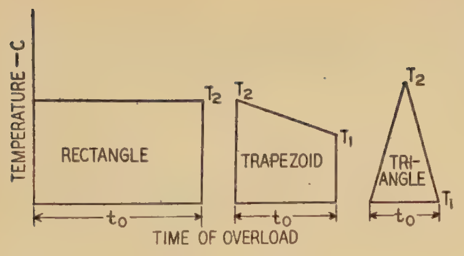

Figure 7. Temperature areas applicable to integration by:

Equation 2 for rectangles

Equation 3 for trapezoids and triangles

$$A = \int_0^{t_0} e^{0\cdot088\left[T_1+(T_2-T_1)\frac{t}{t_0}\right]}\,dt$$

$$= e^{0\cdot088T_1}\int_0^{t_0} e^{0\cdot088(T_2-T_1)\frac{t}{t_0}}\,dt$$

$$= \frac{e^{0\cdot088T_1}t_0}{0.088\,(T_2 - T_1)}\left[e^{0\cdot088(T_2-T_1)} - 1\right]$$

$$= t_0\left[\frac{e^{0\cdot088T_2} - e^{0\cdot088T_1}}{0.088\,(T_2 - T_1)}\right] \qquad (3)$$

Examples

1. FIVE MINUTE LOAD

For illustrative purposes the aging for the five-minute load, shown in figure 4, will be worked out in detail.

The temperature rise (found by trial) is 149 − 25 = 124 degrees centigrade. By figure 1 the rise in five minutes is 75 per cent of constant and at, say, three-minutes is 55 per cent of constant. Then the rise at three minute period (of the five-minute load) should be $\frac{55}{75}$ = 73.3 per cent of 124 degrees or 91 degrees centigrade. 91 + 25 = 116 degrees actual temperature. The other points on the curve are worked out similarly.

As the cooling is a function of the watts per pound of copper at the instant load is removed, it is necessary to convert the rise in terms of watts per pound. A rise of 124 degrees represents a loss of 275 watts per pound by figure 3.

By figure 2 the cooling in one minute is 45 degrees. 149 − 45 = 104 degrees temperature at the six-minute point. The cooling for two minutes is 70 degrees and 149 − 70 = 79 degrees centigrade temperature at the seven-minute point.

The next step is to resolve the temperature curve into a triangle of approximately the same area, especially the top portion where the aging is most severe.

The triangle shown by dashes has a base of nine minutes and a peak temperature of 149 degrees centigrade.

By substituting in equation 3 and letting $T_2 = 149$, $T_1 = 25$, and $t_0 = 9$,

$$A = 9\left[\frac{e^{0\cdot088\times149} - e^{0\cdot088\times25}}{0.088\,(149 - 25)}\right]$$

$$= 9\left(\frac{490{,}000}{10.9}\right) = 405{,}000 \text{ units.}$$

2. THIRTY-MINUTE LOAD.

The aging for the 30-minute load shown in figure 4 is as follows

$$A_{15} = 15e^{0\cdot088\times112} = 282{,}000$$

$$A_{10} = 10\left[\frac{e^{0\cdot088\times112} - e^{0\cdot088\times100}}{0.088\,(112 - 100)}\right] = 116{,}000$$

$$A_5 = 5\left[\frac{e^{0\cdot088\times90} - e^{0\cdot088\times25}}{0.088\,(90 - 25)}\right] = 2{,}400$$

400,400 total units.

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1. LOADING TRANSFORMERS BY TEMPERATURE, V. M. Montsinger. AIEE TRANSACTIONS, volume 49, 1930, page 776.

2. PREDETERMINATION OF SELF-COOLED, OIL-IMMERSED TRANSFORMERS BEFORE CONDITIONS ARE CONSTANT, W. H. Cooney. AIEE TRANSACTIONS, volume 44, 1925, page 611.

3. COOLING OF OIL-IMMERSED TRANSFORMER WINDINGS AFTER SHUTDOWN, V. M. Montsinger. AIEE PROCEEDINGS, volume 36, part 1, 1917, page 711.

A New Correlation of Sphere-Gap Data

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ASSOCIATE AIEE

Synopsis: The similarity principle for electrical discharges is used to correlate the most recent AIEE sphere-gap data for both positive and negative impulses. Empirical formulas are developed from which the entire range of data can be calculated to within about 1.5 per cent. Some practical results of this study are:

1. Spark-over curves for each value of spacing to diameter ratio are straight lines when plotted to logarithmic scales, at least to within the certainty of the present data.

2. A spark-over voltage chart covering the entire useful range of sphere sizes, spacings, and air densities can be constructed easily.

3. New air-density correction factors are derived which differ appreciably from those previously published.

Introduction

THE SPHERE GAP, widely used for measuring high voltages, is not an absolute standard; that is, its performance cannot be calculated from fundamental considerations. The standard calibration is based on measurements mainly in terms of low-voltage standards through the use of potential transformers or potential dividers. The curves for the eight standard sphere sizes are commonly regarded as independent entities each relying for its accuracy on a separate testing program. Knowledge of an orderly relationship between the curves would fulfill a definite need. It is the purpose of this paper not only to show that there is indeed such a relation but that it is of surprisingly simple form. A direct calculation by classical electrostatic theory is not feasible because for air the puncture strength, or maximum gradient just prior to spark-over, different for each electrode configuration and spacing, is known only through the reverse calculation from experimentally determined spark-over curves. Nor is the present knowledge of the physical mechanism of sparking sufficiently exact to form the basis for accurate calculations. Thus the sphere-gap calibrations are the result of direct experiments, although empirical formulas have been of considerable use in smoothing the data and for extrapolation.

Of the empirical methods developed in the past the best known, due to Peek,[1] gives good results in the range for which it was intended, but, as might be expected, fails when used for extrapolation far outside this range. Its basis is an empirical formula for the maximum gradient prior to spark-over involving sphere radius and air density, but not spacing as it probably should. When both spheres are insulated the spark-over voltage is calculated from this gradient by classical electrostatic theory, and when one sphere is grounded, by an empirical method. The AIEE standard air-density correction factors were calculated from Peek's gradient formula.

Bellaschi and McAuley[2] have smoothed and extrapolated their data by making use of their discovery that for each constant ratio of sphere gap opening to sphere diameter plots of average gradient against the logarithm of sphere diameter are essentially straight lines for sphere diameters above 25 centimeters. Later Bellaschi[3] elaborated on this method giving empirical formulas with numerical values for their parameters.

The new method which is the subject of this paper, while empirical, appears to have a wider range of usefulness and greater simplicity than methods published heretofore. It is based on the principle of similarity for electrical discharges, a principle well established in the field of physics, but whose power seems not to have been fully appreciated by engineers in this country.

The Principle of Similarity for Electrical Discharges

The principle of similarity for electrical discharges, a generalized form of Paschen's Law, states that in a given gas "Geometrically similar systems will discharge at the same potential if the products of their leading dimension and mass of gas per cubic centimeter are the same; or the discharge potential is a function of the product of density and a dimension for similar systems."[4] This law originally deduced from, and since substantiated by direct experimental evidence, the extent of which is mentioned below, has also been shown by Townsend[5] to result from his theory of sparking as the result of cumulative ionization by collision. Applied to an isolated symmetrical sphere gap it means that the sparking voltage V depends only on the ratio of spacing to diameter (S/D), which specifies the geometry, and the product of spacing by air density ($S\delta$). Written symbolically this becomes

$$V = F\left(S\delta, \frac{S}{D}\right) \tag{1}$$

Or alternatively if D instead of S is taken as "the leading dimension," the equation is

$$V = \Phi\left(D\delta, \frac{S}{D}\right) \tag{2}$$

Although the functions F and Φ can be expressed only graphically or empirically, it is evident that the number of independent variables determining V is not three as commonly thought, but two, the combinations $S\delta$ and S/D.

For practical sphere gaps other ratios of dimensions describing the shanks and the position of the gap with respect to grounded surfaces should be included. However, since little is known about the effects of these other

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[1] For all numbered references, see list at end of paper.

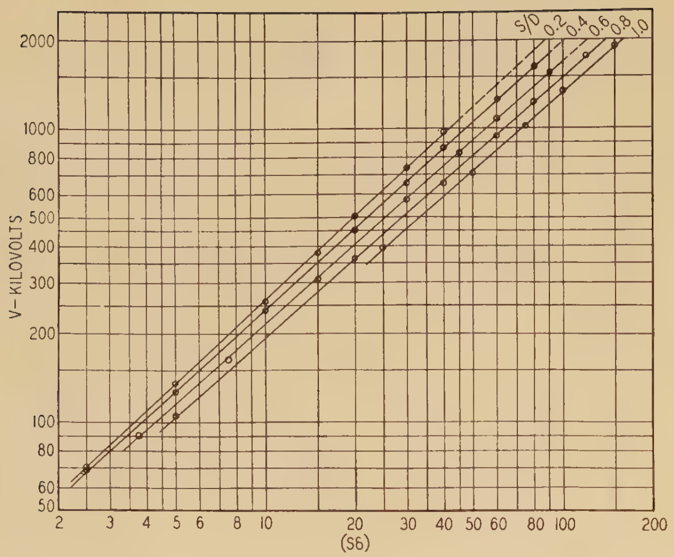


Figure 1. Lines for which S/D is constant

Data from AIEE Revised Standards for Negative Impulse

Table I. Parameters for Equation 3

One sphere grounded: $2 < (S\delta) < 200$; $5 < (D\delta) < 200$

	For Negative Impulse and 60 cycles		For Positive Impulse	
S/D	*K*	*α*	*K*	*α*
0.1	30.10	0.941	30.15	0.941
0.2	29.95	0.940	30.15	0.940
0.3	29.65	0.931	30.15	0.931
0.4	29.25	0.917	30.15	0.917
0.5	28.55	0.904	30.15	0.900
0.6	27.45	0.895	30.10	0.884
0.7	26.21	0.891	29.70	0.872
0.8	24.96	0.888	29.00	0.865
0.9	23.69	0.886	28.00	0.860
1.0	22.44	0.885	27.00	0.855

Table II. Comparison of Calculated and Standard Spark-Over Voltages, Negative Impulse and 60 Cycles

Upper figures are calculated; lower figures are from AIEE Standards[8]

S/D	*D*							
	6.25	12.5	25	50	75	100	150	200
0.1			71.3	136.9	201	263	385	504
			72	136	200	261	383	506
0.2		70.9	136.0	261	382	501	733	960
		70.8	136	260	380	504	736	973
0.3	53.2	101.5	193.5	369	538	703	1,026	1,341
	53.8	100.6	192	367	528	700	1,040	1,346
0.4	67.8	128.0	242	456	662	861	1,249	1,626
	68.8	127.0	241	451	653	862	1,254	1,635
0.5	80.0	149.7	280	524	756	981	1,415	1,835
	81.0	147.5	278	519	751	985	1,410	1,857
0.6	89.6	166.6	310	576	828	1,072	1,540	1,992
	90.3	164.5	309	573	827	1,084	1,552	2,027*
0.7	97.6	181.1	336	623	894	1,155	1,657	2,141
	98.2	179.5	338	615	890	1,163	1,662	2,169*
0.8	104.2		357	661	947	1,222	1,752	2,263
	105.5		362	651	945	1,234	1,760	2,293*
0.9			374	691	989	1,276	1,828	2,359
			379	681	992	1,295	1,820	2,395*
1.0			387	716	1,024	1,321	1,892	2,440
			393	707	1,025	1,338	1,900	2,475*

* Extrapolated by AIEE, not used in determining parameters.

geometric ratios, except that in practice they are usually small, they are ignored here. Necessarily F and Φ depend on whether both spheres are insulated or one is grounded and if so on polarity as well. Except for density, whose primary significance in this connection is that it is inversely proportional to the mean free path, other properties of the air, such as its humidity, have no appreciable effect on V within the range of S/D used in measurement practice.

Researches on the similarity principle for spheres are well summarized by Whitehead,[4] Thomson,[6] and Bowker.[7] V has been shown to depend only on the product $(S\delta)$, with S/D constant, independently of S, temperature and pressure. With hydrogen and nitrogen the temperature was carried to over 800 degrees centigrade at pressures from 0.25 to 2 atmospheres. In air the law holds up to at least 300 degrees centigrade, and at room temperature from pressures of a few millimeters to about 10 atmospheres, above which there is a departure. The spheres used were small, from 1 to 2.5 centimeters in diameter, and S/D was usually less than 0.2 although in some cases as high as 0.5. Taking $\delta = 1$ for normal atmospheric conditions of 760 millimeters and 25 degrees centigrade, the maximum $(S\delta)$ attained was about 2.0 for which approximately $V = 60$ kv.

Correlation of the Data

As a consequence of the usual testing procedure, sphere-gap data are customarily presented as separate curves or tables of V vs. S, $(\delta = 1)$, for each size of sphere. Variations in δ are taken into account by means of tabulated correction factors. Three independent variables S, D, and δ are thus considered in determining V. However, as shown here by the similarity principle, V is really a function of only two independent variables, the combinations $(S\delta)$ and S/D. A function of two variables is not hard to tabulate, but it is even easier to show graphically on a chart. A number of forms of chart were tried in an effort to find one that would be not too large and still include the desired range of variables, easy to read accurately, and easy to construct.

In the course of this study it was discovered that, to within the certainty of the best data available, curves of V vs. $(S\delta)$ for constant S/D plotted to logarithmic scales are *straight lines* over the entire useful range of sphere gap

Figure 2. Parameters in the formula $V = K(S\delta)^{\alpha}$

One sphere grounded; both impulse polarities

$2 < (S\delta) < 200$
$5 < (D\delta) < 200$

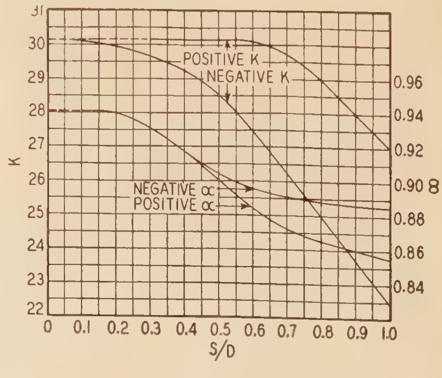


Table III. Comparison of Calculated and Standard Spark-Over Voltages, Positive Impulse

Upper figures are calculated; lower figures are from proposed AIEE standards[9]

S/D	D							
	6.25	12.5	25	50	75	100	150	200
0.3	54.1	103.2	196.8	375	547	715	1,043	1,364
	54.3	101.7	196	374	548	715	1,055	1,364
0.4	69.9	131.9	249	470	682	888	1,288	1,677
	69.3	132.3	252	474	687	888	1,293	1,671
0.5	84.1	156.9	293	546	787	1,020	1,468	1,902
	81.8†	158.0	296	547	786	1,024	1,453	1,896
0.6			330	609	871	1,123	1,607	2,073
			334	605	870	1,124	1,597	2,069*
0.7			360	660	939	1,207	1,719	2,209
			364	655	939	1,209	1,718	2,220*
0.8			387	705	1,001	1,284	1,823	2,339
			390	698	999	1,284	1,824	2,360*
0.9			407	740	1,048	1,342	1,902	2,437
			409	732	1,046	1,344	1,902	2,464*
1.0			423	766	1,083	1,385	1,958	2,505
			426	738†	1,081	1,390	1,944	2,543*

* Extrapolated by AIEE, not used in determining parameters.
† Not used in determining parameters.

testing. For examples, see figure 1. These curves are described by the empirical equation

$$V = K(S\delta)^{\alpha} \tag{3}$$

Where K and α are parameters depending only on the ratio S/D and the polarity. The variation of these parameters with S/D is shown in table I and figure 2, for one sphere grounded and both impulse polarities.

The source of the data for 60-cycle and negative impulse voltages is the partial revision of AIEE Standards No. 4 published in July 1936,[8] and that for positive impulse voltages is a part of the same revision as yet unpublished.[9] The revision is based mainly on the extensive researches of Bellaschi and McAuley[2] and of Meador.[10] Points at desired values of S/D not appearing in the tables were obtained from plots. Using values of S/D for each tenth up to 1.0, K and α were adjusted to best fit the data subject to the condition that curves of K and α against S/D should be smooth. A large scale logarithmic plot was used to obtain preliminary values of K and α which were then refined by successive calculations using logarithms and a computing machine.

The data used and the corresponding calculated values are shown together in tables II and III for the range of conditions defined by $(S\delta) > 2.0$; $6.25 < D < 200$; $S/D < 1.0$; and $\delta = 1.0$. As to accuracy, a comparison of the calculated values and the data for the 116 points given in the tables reveals that 83 agree to better than 1 per cent, 28 to between 1 and 1.5 per cent, and 3 to between 1.5 and 1.9 per cent. Two values for positive impulse are disregarded entirely because they are so far out of line as to be almost certainly in error.

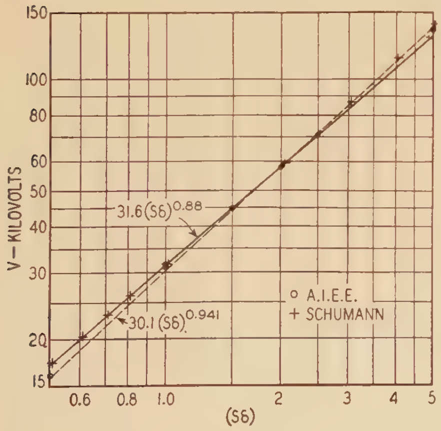
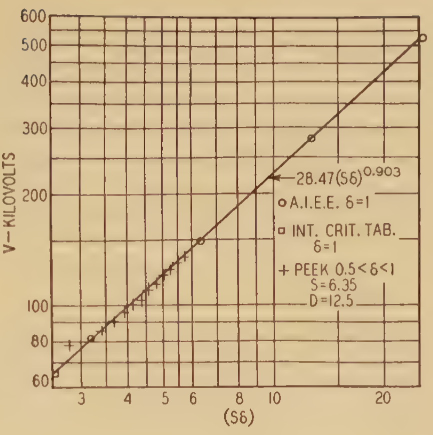


Figure 3. Comparison of formulas for use above and below $(S\delta) = 2.0$; $S/D < 0.2$

Figure 4. Agreement of Peek's low-density tests with AIEE Standard values for $\delta = 1$ and with the new formula for $S/D = 0.508$



When $(S\delta) < 2.0$ calculations using the parameters of table I no longer fit the data so closely, the departure at $(S\delta) = 1.0$, $S/D = 0.1$ being nearly 5 per cent. In this region the true curves to logarithmic scale depart appreciably from linearity although the curvature is still not great. In the range $0.4 < (S\delta) < 2.0$; $S/D < 0.2$, the formula

$$V = 31.6(S\delta)^{0.88} \tag{4}$$

gives a good approximation to data collected by Schumann[11] for a uniform field, $S/D = 0$, and to the few AIEE data in this range. These data, equation 4, and the line for $(S\delta) < 2.0$ and $S/D = 0.1$ are plotted for comparison in figure 3.

The data discussed so far are for values of $(S\delta)$ when $\delta = 1$, that is for standard atmospheric conditions. Test data for $\delta \neq 1$ and $(S\delta) > 2.0$ are not easily found in the literature. Some reported by Peek[1] for 12.5-centimeter spheres, one grounded, spaced 6.35 centimeters ($S/D = 0.508$) at relative air densities down to about 0.5 are plotted in figure 4. There is close agreement between these points and the line defined by equation 3 with the parameters for $S/D = 0.508$ read from figure 2.

Sphere-Gap Spark-Over Chart

The sphere-gap function, F in equation 1, can be mapped to the best advantage on a chart whose co-ordinates are V and $(S\delta)$ to logarithmic scales. Curves of V against $(S\delta)$ for constant S/D, spaced at convenient intervals, are then, to the present certainty of the data, the perfectly straight lines whose parameters K and α have been given. Curves of constant $(D\delta)$ can be drawn through points easily located on the constant S/D lines. In addition to simplicity of construction the logarithmic scales give compactness together with constant accuracy for all parts of the chart. A chart for negative impulses and 60 cycles is shown to a small scale in figure 5.

In working out settings from the chart the following rules are evident. For a given fixed gap with varying air density, changes take place along a line of constant S/D. For a particular sphere size at a particular air density, changes take place along a curve of constant $(D\delta)$ as the spacing is varied.

Air-Density Correction Factor

For tests at relative air densities other than unity the standard table values of spark-over voltage, which are for $\delta = 1$, 760 millimeters and 25 degrees centigrade, have heretofore been corrected by means of the multiplying factors given in AIEE Standards No. 4. These factors, which are identical with those calculated by Peek[1] and those recommended by the I.E.C.[12] are tabulated for each size of sphere and for $0.50 < \delta < 1.10$. No account is taken of any effect due to changes in S/D, nor of polarity since they are for 60 cycles.

The method advocated here is based on the similarity law and contained in the chart, figure 5. For a given S/D the spark-over voltage for any δ is read from the curve of V vs. $(S\delta)$, which may have been found originally for some other δ. If a chart is not available, then with the aid of the empirical formula 3 the spark-over voltages of a particular sphere gap at two different densities are related by

$$V_2 = V_1 \left(\frac{\delta_2}{\delta_1}\right)^{\alpha} \tag{5}$$

The air-density correction factor for use with the standard values is thus simply $(\delta)^{\alpha}$, and depends not on D but on S/D and the polarity. The new factors for each polarity and one sphere grounded are shown in table IV. That they should depend on the polarity of the unsymmetrical gap is not surprising when it is remembered that positive and negative discharges have distinctly different properties. A comparison with the present standard factors shows for negative impulses or 60 cycles the possibility of a maximum difference between them of about 1 per cent at $\delta = 0.9$ increasing to about 5 per cent at $\delta = 0.5$. In general, the direction of the difference depends on both D and S/D. When $\delta < 1.0$ the new factors for

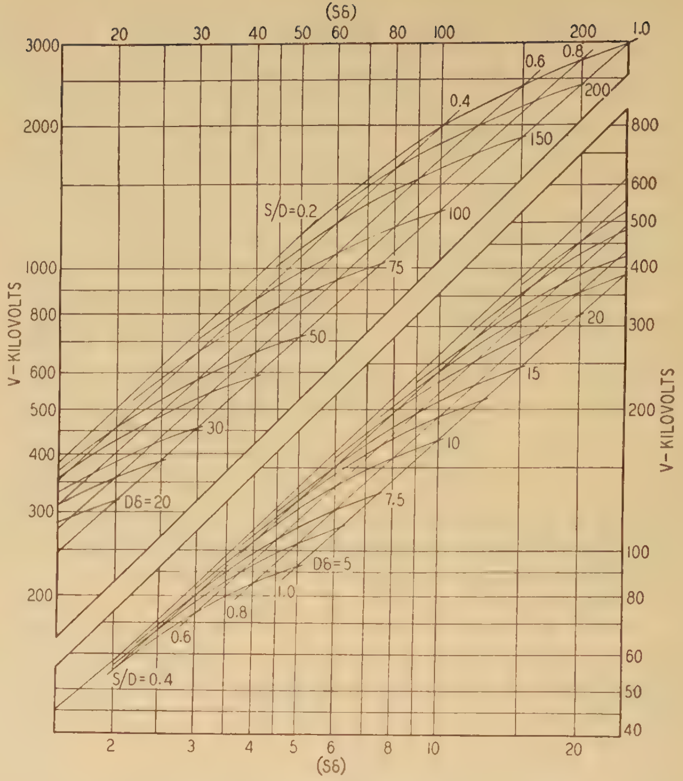


Figure 5. Sphere-gap spark-over chart

One sphere grounded; negative impulse and 60 cycles

Table IV. Air-Density Correction Factors; One Sphere Grounded

Where they differ, factors for positive impulse are printed below

δ	$2.0 < (S\delta) < 200$									$0.4 < (S\delta) < 2.0$
	S/D 0.2 and less	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	0.2 and less
0.50	0.521	0.524	0.530	0.534 0.536	0.538 0.541	0.539 0.546	0.540 0.550	0.541 0.551	0.541 0.553	0.543
0.55	0.570	0.573	0.579	0.582 0.584	0.585 0.589	0.586 0.593	0.588 0.596	0.589 0.598	0.589 0.600	0.591
0.60	0.618	0.621	0.626	0.630 0.631	0.633 0.636	0.634 0.640	0.635 0.643	0.636 0.644	0.636 0.646	0.638
0.65	0.667	0.670	0.674	0.678 0.679	0.680 0.683	0.681 0.687	0.682 0.689	0.683 0.690	0.683 0.692	0.685
0.70	0.715	0.717	0.721	0.724 0.725	0.727 0.729	0.728 0.732	0.729 0.734	0.729 0.736	0.729 0.737	0.731
0.75	0.763	0.765	0.768	0.771 0.772	0.773 0.775	0.774 0.778	0.775 0.780	0.775 0.781	0.775 0.782	0.776
0.80	0.811	0.813	0.815	0.817 0.818	0.819 0.821	0.820 0.823	0.821 0.824	0.821 0.825	0.821 0.826	0.822
0.85	0.859	0.860	0.862	0.864	0.865 0.866	0.866 0.868	0.866 0.869	0.866 0.870	0.866 0.870	0.867
0.90	0.906	0.907	0.908	0.909 0.910	0.910 0.911	0.911 0.912	0.911 0.913	0.911 0.913	0.911 0.914	0.911
0.95	0.952	0.953	0.954	0.954	0.955	0.956	0.956	0.956 0.957	0.956 0.957	0.956
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.05	1.047	1.046	1.046	1.045	1.045 1.044	1.044 1.043	1.044 1.043	1.044 1.043	1.044 1.043	1.044
1.10	1.094	1.093	1.091	1.090	1.089 1.088	1.089 1.087	1.088 1.086	1.088 1.085	1.088 1.085	1.088

6.25-centimeter spheres are smaller than the old over the whole range of spacing, while for 100-centimeter spheres they are always larger. The possible differences between the new positive impulse factors and those now in Standards No. 4 are even greater, about 1.3 per cent at $\delta = 0.9$.

Concluding Remarks

The method given here for calculating the standard sphere gap spark-over voltages has an accuracy of better than 1.5 per cent, which is well within the tolerances in this field of measurement. AIEE Standards No. 4 specifies an accuracy of 2 per cent for tests carried out in accordance with its instructions, while in the revised standards this figure has been increased to 3 per cent in recognition of the difficulty of attaining the ideal conditions in practice.

It is possible that in many cases the new air-density correction factors are enough different from those now in use to materially reduce the discrepancies between the results of the various standardizing laboratories.

It is suggested that future standardization tests be guided by the facts brought out here; that in accordance with the similarity principle the basic variables are S/D and $(S\delta)$; and that with S/D held constant the relation of V to $(S\delta)$ is a very simple one. Even though more precise tests may show the empirical formula 3 not quite exact, the curves of constant S/D to logarithmic scale must be so nearly linear that they can be firmly established using only four or five wisely chosen sphere sizes.

List of Symbols

V = Spark-over voltage in kilovolts crest.
D = Diameter of sphere in centimeters.
S = Spark-over distance between spheres in centimeters.
δ = Relative air density; unity for 760 millimeters and 25 degrees centigrade
K = Empirical coefficient depending on S/D.
α = Empirical exponent depending on S/D.
F, Φ = Functions of unknown mathematical form.

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Electrical Equipment for Modern Urban Surface Transit Vehicles

By S. B. COOPER

Synopsis: This paper reviews modern urban surface transit developments, traces the reasons for the changes, and outlines some of the problems involved and their solution.

THE CHANGING conditions that have produced such marked developments in public urban transportation vehicles during the past ten years have naturally brought about corresponding changes and developments in the electrical propulsion equipment.

During the period from 1926 on, the increasingly serious competition from the private automobile and the gas bus made it more and more evident that the transit industry could not continue to compete successfully with these newer forms of transportation while still using the tools and methods developed during the previous decade with little change up to that time other than detail improvements.

The need became increasingly apparent about this time for vehicles which would do several things:

1. Provide a faster, smoother ride.
2. Provide a more attractive vehicle from the standpoint of passenger appeal—finish, seats, lights, quietness, etc.
3. Reduce operating costs.

These requirements led to a greatly accelerated rate of development in cars, trolley coaches, and gas electric busses, and in the electrical equipment for each of these vehicles.

The first major efforts of this period in improvements in cars lay along the lines of:

1. Reduced weight.
2. Lower floors and steps.
3. Reduction in unsprung weight.
4. Reduction in noise.
5. Improved braking.
6. Increased acceleration.
7. Automatic acceleration.
8. Better appearance.

These objectives led to a period of intensive development from 1927 to 1930 during which were introduced *WN* double reduction, single reduction, and worm type gear units, which in turn called for and made possible the 300 volt, high-speed spring-supported motor now so generally accepted. New ideas were introduced along truck and body lines, largely to take advantage of features made possible by the new motor and drive developments. Also the need for more rapid acceleration brought about the introduction of the variable automatic controls of different types—it being generally felt that the higher rates and the general adoption of one man operation made automatic acceleration very desirable if not essential.

This period of intensive development, with aims sometimes paralleling and sometimes in conflict, together with a growing realization of the urgent need for some degree of standardization, no doubt had a part in the organization during 1930 of the Presidents' Conference Committee.

Other papers deal with the history and accomplishments of this committee; suffice it to say that the results obtained in the past two and a half years fully justify its activity.

Following the early period of investigation and research by the committee, the problem presented to the designers of electrical equipment was about as follows:

1. To produce a 55-horsepower motor lighter and smaller than anything so far achieved.
2. A control equipment which would permit automatic acceleration rates up to 4.75 miles per hour per second so smooth that even standing passengers would not be able to detect individual notches.
3. The motor and control equipment to be so designed as to take the major share of braking duty away from the shoe on the wheel, and to be capable of producing in conjunction with the air-actuated wheel brakes and the magnetic track brakes smooth braking rates up to 4.75 miles per hour per second in service applications and up to 8 or 9 miles per hour per second in emergency.

Standardized mounting and housing arrangements were called for, with means for recovery of accelerating and braking resistor losses for car heating when required.

Two different equipments are now available to produce these results. It is felt that detailed description of the apparatus and functioning is beyond the scope and purpose of this paper—these details are available to those interested. The electrical manufacturing companies have produced equipment fulfilling the objectives established by the committee. The 55-horsepower 300-volt motors weigh about 700 pounds each in contrast to 2,185 pounds for an axle-hung type motor of corresponding capacity. The motor barrel diameter is 15 $^3/_4$ inches and the length over the housings about 25 inches. Figure 1 shows a motor of this type; such motor designs have been made possible by the use of high-temperature insulation, improved antifriction bearings, and perhaps most of all by developments in armature and commutator design and construction which permit peripheral speeds way beyond anything considered possible ten years ago.

It happens that during the period from 1926 to 1930 there was also a rapid and intensive development in a-c motors for steam-railroad electrification, leading up to the Pennsylvania electrification program of 1931. Many of the improvements, processes, and principles worked out

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in connection with these a-c motors were found directly applicable to d-c motors as well. This contributed greatly to the development of the light-weight high-speed motors which we have today for cars, trolley coaches, and gas and oil electric busses.

For instance the technique of application of antifriction bearings to railway motors underwent tremendous development during this period. The recognition of the necessity for careful choice and maintenance of adequate internal clearances in these bearings under railway motor conditions might be cited. The growing use of cylindrical roller bearings is at least in part due to the ease and accuracy with which the internal clearance after assembly can be measured.

The extreme importance of keeping lubricant *in* and dirt *out* of these bearings has become more generally understood. The use of the steel labyrinth type of seal without rubbing or wearing surfaces has aided greatly in the accomplishment of these objectives without the necessity for frequent renewals due to wear on any type of rubbing surfaces at the high speeds used in these bearing applications. Another important improvement in this respect, especially from the maintenance point of view is the use of "cartridge" type bearing construction which permits the removal, storage, and replacement of complete armatures without opening the bearing enclosures and the resultant risk of getting dirt into the bearings.

The a-c motor development also added greatly to our knowledge on such subjects as permissible limits in armature-field ampere-turn ratios, pole widths and shapes, pole-tip shapes and spacings, etc., all of which has contributed to a marked degree to the design of the d-c motor as well.

Noise reduction has become increasingly important; noises in electrical machines can be generally grouped into three classes—windage, magnetic, and bearing. As the result of careful study, air paths and air foil shaping of surfaces directing air flow are better understood and proper attention to these details has resulted in marked improvement. Intensive research has led to a better understanding of the sources of and remedies for magnetic noise. The use of skewed slots, or more recently, careful selection of number of slots in combination with proper pole shape and spacing, have both been found effective in reducing or eliminating magnetic noises. Bearing noise is of course largely a matter of proper control of bearing clearances and lubrication.

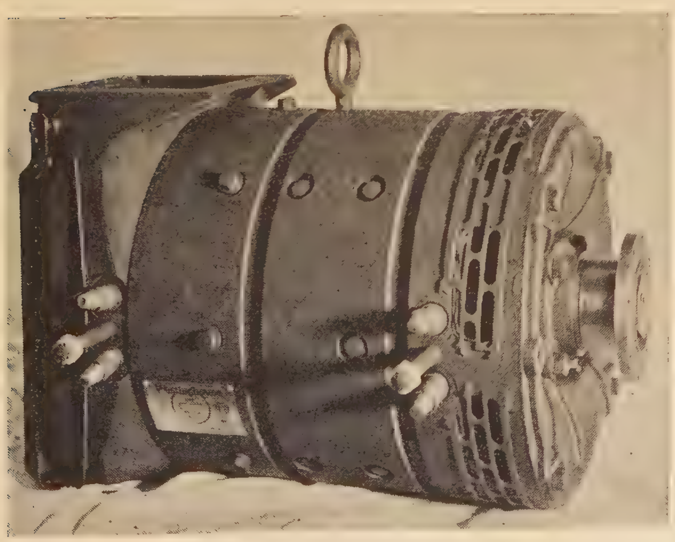

Figure 1. Motor for PCC car

The urge for smaller and lighter machines for a given rating forced the designers years ago to look for insulating materials which would stand operating temperatures beyond the limits of treated cotton insulation. This led to the use of mica and asbestos in various forms, and tremendous improvements have been made in the technique of manufacture and application of mica and asbestos insulation to railway motors. Unfortunately, both of these materials are natural products, found in only comparatively limited quantities in grades suitable for electrical insulation; like all natural products their characteristics are not uniform, and there is always the question of the ultimate exhaustion of available sources of supply. In addition, there are certain inherent limitations in these materials that at least so far have not been entirely overcome. For instance, both mica and asbestos are mechanically weak and therefore require, for practical manufacturing reasons, the use of certain carrier materials to add mechanical strength and stability during handling and application. Mica, being inherently a flaky material, is usually built up on a paper or silk tape carrier, and is somewhat difficult to apply satisfactorily to small conductors. Asbestos tapes are necessarily built up with cotton or silk cross threads to give mechanical strength, and there are certain definite limits in minimum thickness below which asbestos insulation cannot be obtained.

There has recently been developed a new material for high temperature insulation which affords very great promise—glass tape. This is a fabric type tape woven from threads of spun glass. It has most astonishing flexibility and strength, can be made in almost any required thickness down at least to 5 mils and of course has wonderful heat resisting and dielectric properties. Being a synthetic product its properties can be closely controlled, and the raw materials from which it is made are available in almost unlimited quantities. It is now beginning to be used in these types of high-speed railway motors, and it holds great promise as a means of still further improving designs.

A most important factor in the design and production of these small light-weight motors is the very large increase in limiting peripheral speeds of armatures and commutators as compared to previous practices. Here again the fundamental development work carried out on the a-c motor was directly applicable to these small d-c motors. It is not so very many years ago that 7,000 feet per minute on armatures and 5,000 on commutators were considered top limits. Now we are going up to 12,000 and 9,500, respectively. A number of factors are involved in this increase. Improved bearings and better understanding of bearing application, improved methods and materials for banding and wedging, better methods of dynamic balancing, and perhaps most important of all, very marked advance in technique of design and building commutators have all contributed their share to the final results.

Armatures of the type used in these applications are balanced to within 20 inch-square ounces. The two planes at which corrective balance weights are applied are 11 inches apart, and the radius at which weights are applied is $4^1/_2$ inches, so it can be seen that the limiting weight tolerance is about two-fifths ounce.

Commutator improvements have been principally along the lines of better understanding of the forces acting on the bars at high speeds and temperatures, and the absolute necessity of maintaining a practically true cylindrical surface throughout the entire range of operating speeds and temperatures. We have come to realize that a very large percentage of our commutation and current collection problems are mechanical in nature, and to successfully meet them we must keep an intimate and continuous contact between the bars and the brush. When a real commutator expert speaks of a rough commutator he probably means one where the variation in radius from one bar to the next may be as great as four ten-thousandths of an inch.

A commutator is made up of a steel spider and V rings, mica bushing and V ring insulation, and copper and mica bars. All these materials have widely divergent mechanical and temperature characteristics, and their behavior under repeated cycles of speed, heating, and cooling is decidedly different. Successful solution of the problems involved requires the use of very high grade alloy steels for the bushings and V rings, extraordinarily careful selection and treatment of the copper and mica, and extremely close control of and tolerances in the entire process of building and seasoning. Seasoning has been found to be an absolutely essential final step in commutator manufacture. Each one is put through repeated cycles of spinning under heat, grinding and tightening until the entire structures acquires the necessary mechanical stability and the ability to "stay put" in service.

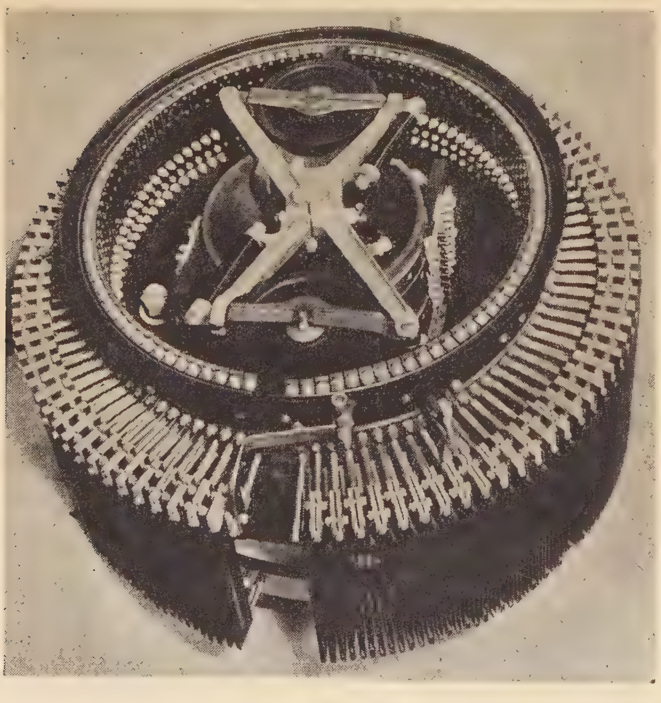

Figure 2. Accelerator for PCC car control

While the subject of commutation is under discussion another related important factor should be mentioned. Under all conditions, but particularly at the high speeds here involved, commutator and brush performance and life are very seriously affected by the presence of dirt in the ventilating air.

Earlier ventilated railway-type motors drew their incoming air directly from the space under the vehicle, with all the street dirt, wheel wash, and whatever else might be present. All this dirt and moisture is extremely bad for commutator and brush performance and life, and also for all the insulation in the machine. In the PCC car where partial or full skirting tends to carry the turbulent swirl of dirty air along under the car, it was felt that improved life and reduced maintenance of brushes, commutator, and coil insulation fully justified an effort to obtain relatively clean dry air for motor ventilation. Flat ducts are built into the body bolster just above the motors. Air is drawn into louvred openings at the outer ends of these ducts, outside the car skirt and practically at floor level. Flexible bellows connect these ducts to the motors.

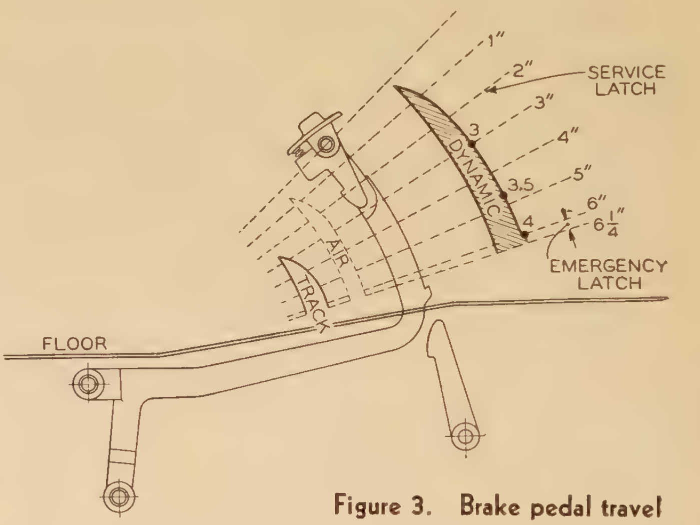

Figure 3. Brake pedal travel

The marked reductions finally achieved in weight and size of these types of motors sometimes lead purchasers to expect corresponding reductions in cost. From the very sketchy outline given above of some of the major problems of these designs and of their solutions, it must be clear that the reductions in weight and size have been possible only by the substitution of higher grade materials and very great increases in labor and tool cost per pound of material used. Price per pound may under some circumstances be a very useful index when applied to the same type of design and construction, but may be wholly misleading if radical differences in design and manufacturing processes are involved.

An important part of the research work carried on by the Presidents' Conference Committee was an investigation of the maximum rates of acceleration and braking and the maximum changes of rate which could be comfortably tolerated by standing passengers. These research tests disclosed some very surprising results, and indicated that rates much beyond those previously considered possible were entirely acceptable, provided they were maintained sufficiently smoothly. Previously existing forms of control varied from 8 or 9 notches in standard *K* types to 14–18 in the then existing automatic types. These gave fairly comfortable accelerations at rates up to 2.5 or 3 miles per hour per second except for an occasional "bump" at transition, but were too rough at accelerations higher than this.

In an eight-notch *K* control, tractive effort increments of the order of 50 per cent of the previously existing value are quite common. In the earlier forms of automatic control this was reduced to about 20 per cent. In the present controls developed for PCC cars the percentage increment in tractive effort per notch is far too small to be perceptible even to standing passengers. Experience has indicated that after the number of notches is increased to about 22, further increases add nothing to passenger comfort, and the selection of number of notches becomes entirely a matter of the limitations of the type of contact device selected.

Actual street experience with the new cars has indicated quite definitely that it is possible for a street car to accelerate and brake as rapidly as a private automobile in the hands of an expert driver, and more rapidly than an average car in the hands of an average driver.

The success of the control equipments developed for these cars may be ascribed to the use of sufficiently large number of notches to eliminate jerks or surges in the acceleration, to the use of actuating means sufficiently sensitive and responsive to maintain smoothly the preselected rates of acceleration and braking, and particularly to means provided to ensure prompt and uniform response of the equipment in dynamic braking.

In one form of equipment the variable resistor device is called an "accelerator" (figure 2) and consists of a cylindrical assembly of resistors, tapped at 97 points, each tap connecting to a spring finger. Successive fingers are pressed into butt type contact with a copper bus by the action of a roller cam carried on an arm rotated by a 32-volt pilot motor through a small worm gear. A sensitive vibrating contact type of limit relay controls the direction and speed of the pilot motor, and thus controls the rate of change of resistance in the main motor circuits. The successive steps are so small in magnitude that individual increments of tractive effort are exceedingly small—far too small to be evident to passengers.

The limit relay setting is changed at the will of the operator by cams on both the brake and the master controllers which are in turn actuated by the foot pedals (or handles on cars arranged for hand instead of foot control) at the operator's position. Thus the one limit relay serves to regulate the automatic acceleration and the automatic dynamic brake, and also to control a function known as "spotting" which is further described below.

The brake controller is actuated from the operator's brake pedal and regulates all three forms of braking, dynamic, track, and air. It consists essentially of three parts mounted on a common shaft. A set of cam-actuated master-controller-type fingers establishes the proper control circuits for the change from motoring to braking. A brush arm rotating around a small fixed commutator regulates the series resistance in the track brake circuit. The third element is a self-lapping type of brake valve. (Figure 3.) The first three inches of pedal travel varies the rate of dynamic braking from a very low minimum rate up to about three miles per hour per second. At the same time the air brake valve is set for a pressure corresponding to the dynamic rate, but this air is blocked off from the brake cylinders by a "lockout" magnet valve which is energized as long as dynamic braking is in effect. When the speed is reduced to the point where dynamic brake begins to fade out, the lockout magnet is de-energized and permits air at the pressure already established at the self-lapping valve to flow to the brake cylinders without conscious action or further pedal manipulation on the part of the operator. The dynamic brake does not fade out suddenly, nor does the pressure in the brake cylinders build up instantly. There is an appreciable and almost equal time interval for both of these functions. As a result, the blend from dynamic to air braking is normally exceedingly smooth and free from any sense of sharp change.

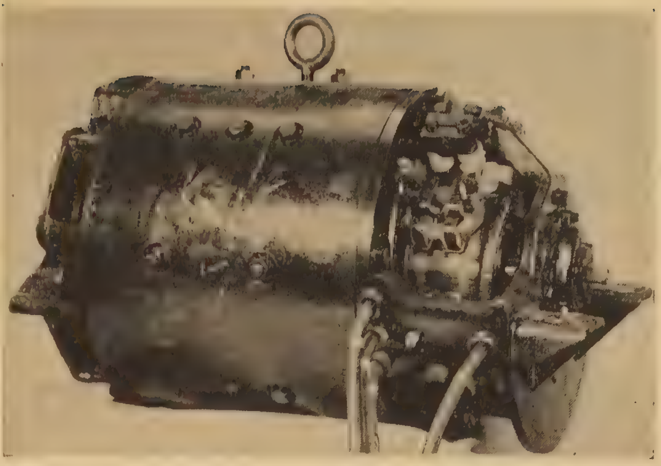

Figure 4. One-hundred-twenty-five-horsepower trolley-coach motor

Pressure of the brake pedal from 3 inches to 6 inches travel superimposes a graduated amount of track braking on top of the dynamic or air brake already obtained, so that rates higher than three to three and one-half miles per hour per second are obtained partially from dynamic and partially from track braking, with air coming in automatically as the dynamic fades out at low speeds.

Depression of the brake pedal to the "full" or emergency positions cuts out the lockout magnet and gives full application of dynamic, track, and air brakes, with automatic application of sand to the rails.

In the other form of equipment available, the variable resistor element consists of a special form of resistors with about 150 taps connected to the bars of a fixed commutator. A brush arm is rotated around this commutator by an air engine, and an ingenious arrangement of transfer contactors permits the use of this variable element twice during acceleration and four times during braking by switching fixed blocks of resistance in or out of the circuit in series with the variable element. In this equipment also a sensitive type of limit relay controls the rate of change of resistance both in motoring and in braking.

In earlier forms of dynamic braking some difficulty was experienced in getting prompt and uniform response at various speeds at the time of application of braking. During dynamic braking the motors are acting as series generators, with voltage varying over a wide range from maximum to minimum speed. In order to quickly establish a given rate of braking the value of resistance in circuit at the time of brake application should therefore be definitely related to speed. For lack of a better name, the means of accomplishing this has been called "spotting" and it is incorporated in both forms of equipment, although somewhat different methods of accomplishing it are used in the two schemes. In general, spotting establishes the correct value of resistance in the circuit, so that either braking or reapplication of power is promptly and smoothly established following a period of coasting.

Early experience with certain of the experimental cars indicated the desirability of more than one form of storage braking, that is, independent of power supply. It was felt that the high speeds of which the new cars were to be capable could not be used effectively unless the operator was fully confident of his abilty to obtain good braking even with bad rail and with an interrupted power supply. This led to the development of a battery excited track shoe. The presence of a battery on the car for this purpose naturally led to the use of the battery for control energy, so that in effect three forms of storage brake are available—in other words even with power off the line or the trolley off the wire, dynamic, track, and air brakes would all function.

The use of a battery required some means of charging. This led to the use of a motor generator set, which was then made to perform the additional functions of driving the air compressor and the 1,250-cubic-feet-minute blower used in conjunction with car heating and ventilation, as described in other papers on this program.

It is evident that the electrical equipment as well as other features of the PCC car incorporate many features radically different from previous practices in the street-car field, and while troubles have been encountered, none of them may be said to be of a fundamental nature, and all of them have been or are being overcome. At least two of the largest operators have expressed themselves as having experienced less trouble with these cars than any lot of new cars they ever placed in service.

Trolley-Coach Equipment

The modern trolley coach may be said to have had its beginning with the Salt Lake installation in 1928. Its growth has been phenomenal—relatively slow at first but now increasingly rapid. There are now in service or on order 1,270 trolley coaches in the United States in addition to "all-service" type vehicles which operate either as trolley coaches or gas electrics.

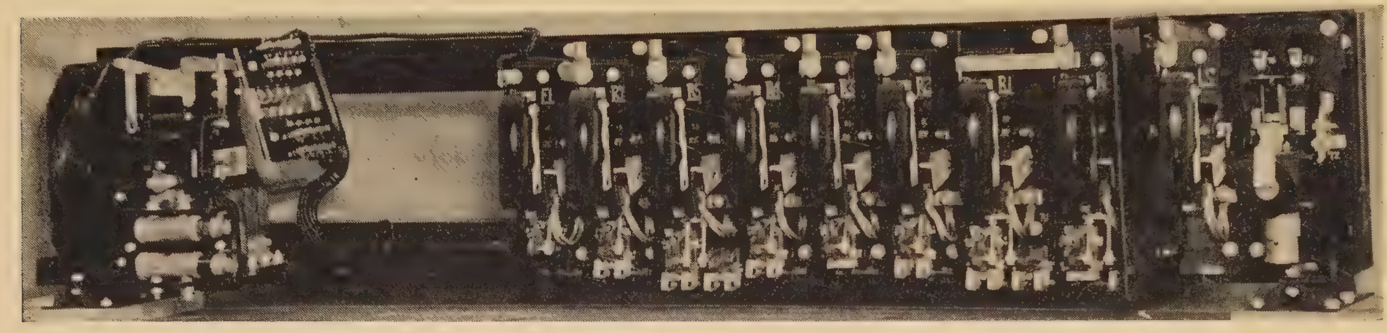

Figure 5. Trolley-coach control panel

The earliest motors used were 50 horsepower, but with increasing weights of coaches and increasing severity of service 65-horsepower motors weighing 785 pounds each became standard—two on 40 passenger coaches and one on 30 passenger.

Control equipments of the variable automatic type have become pretty well standardized for two motor equipments and a simpler nonautomatic type for the 30 passenger single motor coach since these are generally used for lighter service in smaller cities where high rates of acceleration are not so important.

Within the last two years there has been an increasing demand for lighter and simpler equipment for 40-passenger coaches (36 to 44). Development of a suitable single-bowl axle to handle the output of a single motor of sufficient size to give adequate performance on coaches weighing from 17,500 to 20,000 pounds has brought about the development of such motors. There are now in service or on order in the United States 447 trolley coaches using 125-horsepower single-motor equipments.

(Figure 4.) This motor rates 125 horsepower one hour rating and weighs 1,100 pounds, a weight of only 8.8 pounds per horsepower. As in the case of the PCC car motor, this result is partly due to the use of high-temperature insulation and improved designs of roller bearings, but principally to developments in design and manufacture of high-speed armatures and commutators. This motor is particularly noteworthy in this respect as it must necessarily be designed for 600 volts while the PCC motor is wound for 300 volts, two in series on 600.

Another feature of this equipment which makes the motor design even more remarkable is the unusually wide spread between full field and short field curves. There has been a growing conviction for some time in the minds of certain operators that the period of constant-current acceleration is too short, i. e., that acceleration should be carried to higher speed before striking the short field motor curve. The new single-motor 125-horsepower equipment is supplied in two forms, one with a relatively small amount of field shunting, in a single step, and one with three steps of field shunting with a final shunting of over 50 per cent. With the latter arrangement constant-current acceleration is carried up to a speed of 25 miles per hour as compared to 17 miles per hour with the single point shunting. This feature not only permits better schedules but is of great value in passing slower moving vehicles in the street. It also gives higher balancing speeds; while these higher balancing speeds may not often be reached on level runs, the entire speed curve is raised and on hilly routes higher speeds may be maintained on grades.

The single-motor equipment, because of the absence of series-parallel control, has a slightly higher power consumption than the two-motor equipment. In many applications it has been found that the increase in power cost is more than offset by the lower weight and cost, greater simplicity, and reduced maintenance and inspection cost of the equipment. In some cases, where unit cost of power is particularly high or for other reasons, the two-motor equipment may be preferred. Each case must be considered on its own merits and the final selection made by the purchaser on the basis of his own conditions.

(Figure 5.) The development of the single-motor equipment has brought about marked improvement in control equipments. These are now available in forms in which all the equipment except current collectors, motor, and resistor is mounted on a single panel, adapted for either side or rear pocket mounting, and completely wired at the factory. This greatly simplifies installation by the coach builder, and inspection and maintenance by the operator.

It has been found that because of the torque cushioning effect of the tires, a smaller number of notches than on cars gives equally smooth accelerations. The new equipments have 13 or 15 notches including one or three steps of field shunting. Automatic acceleration is universally used on 40 passenger coaches. Marked improvement has been made in simplification of the equipment by improved means of obtaining automatic progression.

In one form of control now available, the progression is entirely by means of electrical interlocking and a sensitive-type limit relay. This has been made possible by the use of "split" operating coils having two sections—a "pull in" winding and a "holding" winding. This scheme greatly reduces the number of interlocks required, and along with the development of a more sensitive current relay removes the obstacles which originally made it necessary to depart from progression interlocking on small capacity equipments—i. e., our inability to put enough interlock fingers on the relatively small contactors required for this size equipment, and the lack of a sufficiently quick response relay.

Another form of control recently developed for single-motor coaches obtains its automatic progression by means of winding up a spring which drives a camshaft through an electromechanical escapement mechanism between the spring and the camshaft.

Some of the features worked out in connection with the PCC car are finding their place in trolley-coach practice as well. In some cases, accelerating-resistor losses are being used for coach heating; in others, definite provision is being made to bring cleaner drier ventilating air to the motors.

The trolley coach is meeting with enthusiastic public response, and is proving itself a vehicle of very great value in that field between the heavy trunk-line route served by street cars and the lighter-service routes served by gas busses.

Gas-and Diesel-Electric Bus Equipment

Another interesting field for the application of electric propulsion equipment is the drive or transmission for gas and Diesel busses. It has been found that mechanical transmissions for large size busses in frequent-stop service are not altogether satisfactory. Frequent acceleration up to the limit of engine capacities imposes severe strains and heavy wear on transmission, clutch, and rear end, and the mechanical labor, time lost, and roughness incident to frequent to gear shifting are serious disadvantages from the standpoint of operator and passenger.

The development of the transit-type bus with rear compartment or under-floor-mounted engines has tended to make the mechanical transmission problems more difficult, and the introduction of Diesel-type engines with their less favorable speed flexibility has also tended to emphasize the advantages of electric drive.

Fundamentally and internal-combustion-type engine performs best as a constant-speed, constant-load prime mover. In urban transit vehicles the power and speed requirements are continually varying over a wide range. The problem presented to the electrical designer is to attempt to reconcile these conflicting characteristics of prime mover and vehicle.

At starting the demand is for high tractive efforts at low speed, which electrically means high current at low voltage; as the speed of the bus increases the current demand gradually falls off and the voltage rises, until at the balancing or free running condition, a low current at high voltage is required. It has been found that these requirements can best be met with a shunt generator with a moderately drooping voltage characteristic, so that the combined motor and generator speed-tractive effort curve approximates a rectangular hyperbola—thus giving very nearly constant horsepower and constant speed loading to the engine. When starting from standstill with the engine idling, a small amount of battery excitation is applied to the shunt field to assist the generator in quickly picking up its load as the engine accelerates. This is cut off by a voltage re-

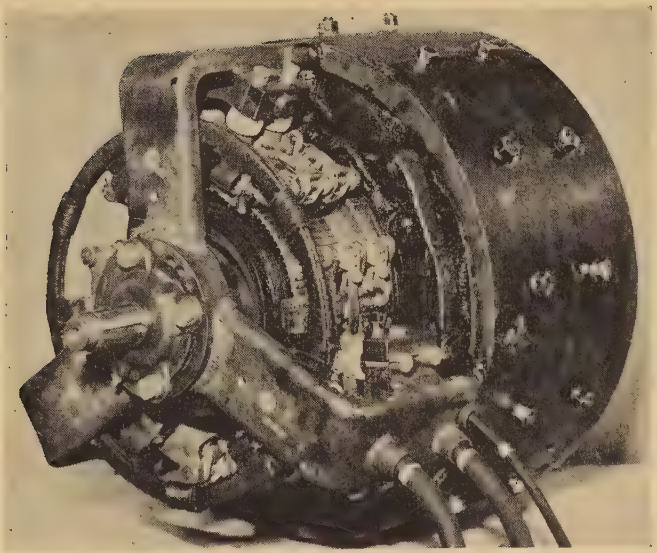

Figure 6. Gas-electric-bus generator

lay, as over excitation of the field for too long a period tends to hold down the engine speed. The prompt pickup charteristic assists in giving electric drive one of its major advantages over a gear shift. With electric drive the engine speed is quickly raised from idling to full speed where it is maintained—thus giving full engine speed and horsepower throughout the acceleration period. This is in marked contrast to a shifting gear mechanical transmission, where each full start consists of three or four successive engine accelerations from idling to full speed, interrupted twice or three times by periods of declutching, shifting, and reclutching so that the average engine speed and power during acceleration is materially below full value, with resultant loss in over-all rate of acceleration.

As bus sizes and weights increase and as service conditions become more severe as a result of increased traffic congestion and the application of busses to heavier-service routes, the tendency is toward larger, more powerful engines. The electrical designer is constantly being called on to provide equipment for larger engine capacities, but of course, is also under continually increasing pressure to produce smaller, lighter, and cheaper motors and generators. Everything that has been said earlier in this paper about the advances in design and manufacturing procedure applies to the machines for electric drive of busses with special emphasis, because electric drive is fundamentally heavier and more expensive than the mechanical drive which it replaces.

In this connection it should be pointed out that, contrary to beliefs apparently held in some quarters, electric drive can never put any more horsepower at the rear wheels than it gets out of the engine. Too often in discussing the performance to be expected from a given bus with electric drive, standard engine curves, taken under conditions vastly different from those which will exist with the equipment as installed in the bus are regarded as showing the engine output under operating conditions. It is important in predicting the performance of busses that account be taken of such items as auxiliaries—fans, battery charging generators, air compressors, etc., and that proper reduction in power delivered to the generator be made. The particular carburetor type and jets with which the equipment is to be used should also be used in making dynamometer tests.

Generators, motors, and control equipment are available for a range of 110 to 180 horsepower in gross engine output, for both single-reduction and double-reduction axles. Figures 6 and 7 show typical generators and motors for gas-or-oil-electric-drive applications.

A particularly interesting form of gas-electric bus is the "all-service" vehicle, developed and widely used on the Public Service Co-ordinated Transport in New Jersey. This vehicle is capable of operation either as a gas-electric or as a trolley coach. As usually built it has a single generator and two motors. The motors are connected in parallel for operation from the generator and in series for operation from the 600-volt trolleys. This vehicle has obvious advantages of extreme flexibility—it may operate over parts of its route where either local ordinances or low traffic density preclude the use of overhead wire, while retaining the advantages of trolley coach operation over heavily traveled sections of the route. It is also available for chartered or other service on unwired routes.

The only essential difference in its electrical equipment from a straight gas-electric is in the requirement of operation from 600-volt trolley, and the provision of current collectors and suitable changeover devices from engine to trolley operation.

We have attempted in this review to give a picture of the recent advances in the design and manufacture of electrical equipment for these public urban transit vehicles—not that these results are final—but rather as a survey of what has been done, and an indication of the direction in which further progress can be expected.

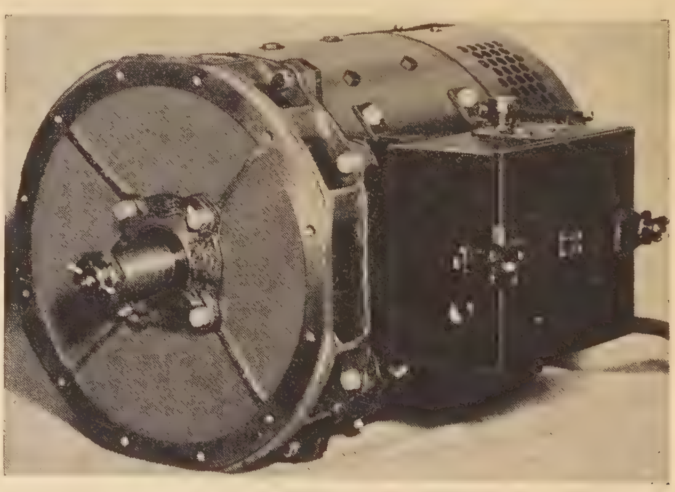

Figure 7. Gas-electric-bus motor

Cities exist and will probably continue to grow—public transportation is an absolutely essential service and must continue to expand and its methods must progress. We confidently expect that electric propulsion will continue to occupy a vitally important place in this field.

Application of Modern Electric Vehicles to Urban Transportation

By C. M. DAVIS
ASSOCIATE AIEE

THE URBAN transportation problem involves the movement of large numbers of city dwellers to and from work, school, or the shopping districts. These movements are frequently concentrated into a few hours in the morning and evening, and are handled largely through city streets, or, in the larger cities, on subway or elevated lines. The corporations handling this business, commonly called "mass transportation," operate under franchises from local authorities. These franchises usually specify minimum service over specified routes.

Transportation by private automobile or in public taxi cabs involves a large number of vehicles for a relatively small number of passengers transported. It would be impossible for our larger cities to function without the organized transportation systems of rapid transit, street railways, or busses. Not only would the cost of daily transportation be greatly increased for the great majority of riders, but the cities themselves would have to be rebuilt, if highways were to be provided of adequate capacity to handle, in small capacity vehicles, the present users of urban transportation systems.

What, then, is the ideal transportation system for our cities? It is one that will move the traveling public at the highest schedule speed consistent with safety; with a minimum of waiting time; with reasonable comfort; with the least interference with other traffic; and at the lowest cost, including fixed charges on the capital investment, consistent with the foregoing requirements.

Urban transportation is handled at the present time by four classes of service — rapid transit lines operating on private rights of way, over or under city streets; surface street railways; trolley coach lines; and gas busses. Each has a proper field which is not only the most logical, but the most economical from the community standpoint, though existing systems do not in every case justify this assumption.

In the small city, where the available traffic on any individual route is limited to 100 or 200 passengers per hour in the direction of maximum movements, which can be handled by small vehicles on 15- or 20-minute headways, the gas bus may be the logical type to use, since it involves a lower investment, and in some respects, lower operating costs than other forms of transit. Busses seating 20 passengers and carrying ten standees, on 15-minute headways, can carry away from a given area 120 passengers per hour, and the installation cost per mile of route will be very small compared to other types of service. With the cheaper types of gas busses of this size, a route giving 15-minute service, may be equipped including garage facilities, for $3,000 to $4,000 per mile. When pioneering into new territory in small or medium sized cities, this is probably the logical equipment to use.

However, routes in many cities are operated with such vehicles on long headways, where a more attractive service might substantially increase riding, and amply justify larger and more attractive units, more frequent headways, or both.

Larger gas busses, seating 30, on 15-minute headways, could handle 180 passengers per hour, and would require an investment of $8,000 to $9,000 per mile of route, including spares and garage. On the same headway, 40 passenger units can carry 240 passengers per hour, and will have an installation cost of approximately $12,000 per route mile.

But at about this point of traffic density, the trolley coach comes into the economic picture. These vehicles have a body and chassis similar to those of the highest grade gas busses, but instead of the engine, clutch, transmission, radiator, gas tank, and battery, they use electric motors and control and take their power from a pair of trolley wires, through poles sufficiently long to permit the vehicle to move 12 to 14 feet to either side of the wires. The simplicity and long life of this type of equipment effects lower maintenance and depreciation as compared with gas busses. Electric power is usually cheaper than gasoline. The overload capacity of its motors, an unlimited supply of power available, and the smoothness of its application make it possible to accelerate at rates far in excess of the most powerfully engined gas bus, and to make faster schedule speeds in frequent stop service.

However, the installation cost of a trackless trolley system is much greater than one operated by gas busses. Its use involves a pole line carrying four trolley wires that may cost $5,000 to $10,000 per route mile to erect, and an investment in substation facilities of from 30 to 40 kw for each vehicle operated, costing $1,500 to $2,000. On 15-minute headways, with 30 passenger vehicles, a trolley-coach system will have an installation cost per route mile about $6,000 higher than a gas-bus system, and with 40 passenger vehicles on five-minute headways, the difference in investment would be around $12,000 per route mile in favor of the gas bus.

But the economic life of the trolley coach should be appreciably longer than that of the gas bus, so its depreciation rate would be less. The line work may be assumed at five per cent or less annual depreciation, and the substation not more than four per cent. Even on this basis, the gas bus system will have an advantage in annual fixed charges for interest and depreciation of from $400 to $700 per route mile. This, however, amounts to but 0.6 cent to 0.8 cent per vehicle mile operated.

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On the other hand, operating records from companies using both types of vehicles indicate that, in the heavier classes of urban service, trolley coaches will save enough in equipment maintenance, power, and garage accounts as compared to gas busses in similar service, to much more than offset their higher fixed charges, and that they will attract more traffic by giving a smoother, quieter, more comfortable, and faster ride to users of the service.

Cost of service, therefore, including fixed charges, will usually be lower for a trolley-coach system if vehicles seating 30 passengers or more are to be used on headways of 15 minutes or less. This is true for new routes. It is even more apparent when an existing street-railway route is changed over to rubber-tired vehicles, for the substation and much of the distribution system is already paid for and installed, so the excess cost of the trolley-coach system over gas busses will be much less than was indicated in preceding calculations, and the relative costs of service are more certain to favor the electrically propelled coach.

As an alternative, where physical, political, or financial factors dictate the use of large-capacity motor busses instead of trolley coaches, the former may be equipped with electric drive, and obtain advantages in faster acceleration, and hence higher schedule speed, greater quietness and smoothness of operation, and a reduction in engine fumes. The electric drive consists of a generator directly connected to the engine, delivering power to a motor geared to the driving axle. Its use eliminates the clutch and gear transmission of the usual mechanical drive, and results in lower maintenance cost. It greatly reduces physical effort on the part of the driver, and provides a faster and more comfortable ride for the passengers.

Diesel engines with mechanical drive, in frequent stop bus service, have developed many mechanical difficulties that are minimized or eliminated when electric drive is installed. In fact, it appears that the successful employment of Diesel engines in passenger busses in urban service is conditioned upon the use of electric transmission. A number of such Diesel-electric busses have been put into operation in the past year, and they are showing such substantial reductions in fuel costs, as compared to gas busses, that it is safe to say many more installations will be made.

One large transportation company has introduced a distinctly new type of rubber tired vehicle using electric drive. This is the so-called "all-service vehicle," nearly 500 of which are in service, and which is primarily a trolley coach, but equipped with gas-electric drive for routes where no trolley wires are available, for use on detours, or for excursion work on Sundays or holidays when not all of the fleet are needed on trolley routes. When beneath the wires, the two motors used on these vehicles are operated in series; when power comes from the engine, the two are placed in parallel across a low voltage generator. They are normally operated as trolley coaches, but under certain conditions have greater flexibility than the straight electric coach.

The standard type of 40-passenger gas busses, so far built in this country, can carry in rush hours, with reasonable comfort, not over 70 passengers, and probably cannot operate at less than 40 second headways without interfering with one another. This means a street capacity of 90 units per hour, carrying 6,300 people in the direction of maximum traffic.

Trolley coaches, seating 40, where they are confined to city streets, are built to larger dimensions and wider aisles, and can carry loads 20 per cent to 25 per cent heavier, so on the same headways they might move 7,600-7,800 passengers per hour.

Under such conditions, the investment required would be about $245,000 per route mile for the gas busses, and $275,000 per mile for the trolley-coach system. From an economic standpoint, a street-railway system would be preferable, despite the expense of track construction, which, in paved streets, may cost $100,000 per mile.

A modern street car, seating 60, can readily handle 120 rush-hour passengers, so 53 cars per hour could carry away the 6,300 assumed for the busses, and 65 per hour equal the capacity of 90 trolley coaches. The rail system would have a lower investment in vehicles, shop facilities, line and substation than the trolley coach, but the cost of track would bring the total investment required up to $320,000, 30 per cent above that of the gas bus, and 15 per cent higher than the trolley-coach system. Due to differences in depreciation rates, the fixed charges on the three systems would be approximately equal. Operating costs on the rail system would be very much lower, due to the smaller number of vehicles, even though their cost per car mile would be appreciably higher. The total cost of service for the rail system, under these conditions, may be assumed as $22,000 less per route mile per year than the trolley coach system, and $35,000 less than the gas bus system, besides causing less street congestion for other vehicles using the street.

As the density of traffic decreases, the advantage of the large-capacity rail car becomes less apparent, and to handle rush-hour traffic requiring 2-minute service with trolley coaches, or 3-minute service with rail cars, the costs of service are equal. Again, it might be pointed out that where tracks are already installed and in good condition, the economic dividing line between the rail and trackless service would be in a much lighter traffic field.

If the street railway be used to its maximum capacity, operating on the 40-second headways assumed for the busses, it could handle 10,800 people per hour in the direction of maximum movement, or three parallel streets with rail lines could handle as much as five parallel-bus, or four trolley-coach routes, leaving 33 per cent to 67 per cent more street space available for other traffic. The relative cost of service would be even more favorable to the rail than in the example to which we previously referred, despite an installation cost for the street railway of nearly $500,000 per route mile.

The foregoing discussion is based on the use of the most modern type of large capacity street cars, equipped to operate at schedule speeds as high as even the trolley coach can perform. Such cars have been developed by the industry within the past three years and are operating in Brooklyn, Chicago, Washington, Baltimore, Pittsburgh, Los Angeles, and other cities. As compared to the slow and antiquated equipment that constitutes the bulk of the rolling stock in most cities today, any type of new vehicle, even gas busses, may be justified on economic grounds and earning power, but we believe that in many cases where gas busses have replaced rail service, it would have been better economics to use modern street cars or trolley coaches.

Now we come to the only system that can handle the volume of traffic of our largest cities, the rapid transit systems operating on private rights of way. These are expensive to build, and their carrying charges are enormous, but so is their carrying capacity. The latest system of this type, the four-track municipal subways built and equipped by the New York Board of Transportation, is arranged to handle 11-car trains, each having a capacity of 3,080 passengers, on 90-second headways, or 123,000 passengers per hour on the express tracks alone. Including the local tracks, the total one-way capacity is probably in excess of 180,000 per hour. The older Interborough lines, using smaller cars and shorter trains, now regularly carry 100,000 to 120,000 per hour at the peaks. Even the latter figure equals the capacity of 11 street railway routes, or of 19 streets filled with busses, and the municipal installation may, at no distant date, carry 50 per cent more. Its cost for construction and equipment will probably average $12,000,000 per route mile, but high as this appears at first glance, it is very low in terms of community benefits compared to many other expenditures intended to expedite the movement of passenger traffic.

Chicago spent $22,000,000 a mile to build a two-level river front marginal way, the well-known Wacker Drive, which has an effective capacity of 2,500 automobiles per hour in each direction, or perhaps 5,000 passengers. Fairmont Parkway in Philadelphia, Michigan Avenue in Chicago, and the Sixth Avenue Extension in New York, roads costing from $14,000,000 to $19,000,000 a mile, are other examples of city expenditures, of greater magnitude than subway costs, to provide faster movement for a relatively small number of people.

The New Jersey State Highway from the Holland Tunnel to Newark Airport cost nearly $6,000,000 per mile to build. Its capacity for auto riders is about 4,500 per hour in each direction, and if one lane in each direction were given over to busses, it would still carry less than 10,000 people per hour, so 12 to 18 such highways would have to be provided to equal the subway usefulness.

Many street widening projects have been undertaken in New York, Brooklyn, Detroit, Boston, and Pittsburgh to relieve vehicular congestion and to expedite traffic, that averaged $6,000,000 per mile, including condemnation of property, and even so, the movement of vehicles through them is less rapid than that of the subway trains.

No form of surface transportation in metropolitan areas can approximate the speed of rapid transit trains. No possible expenditures can be made that will permit the movement of an equal number of people in small, individual vehicles, autos, or busses as fast, or as economically as can the subway.

As compared to its nearest competitor in efficient handling of the heaviest traffic, the street railway using the most advanced equipment, the subway costs twice as much to build, as surface lines of an equal hourly capacity. If we neglect the cost of the street in which the rails are laid. On the face of things, it would appear that difference in first cost penalizes the users of the subway in high fixed charges. This is not a fact, however. Of the $12,000,000 referred to as the subway cost, only $3,000,000 or 25 per cent, went for cars, shops, tracks, power distribution system, signals, lights, etc., on which depreciation must be set up, and the other $9,000,000 went into real estate and construction, in other words, into nondepreciable items. Moreover, the depreciation rate on the track and on the cars is lower than for surface equipment, and calculations indicate that if both systems were financed by 50-year bonds carrying a sinking fund that would amortize the principal in that period, and adequate depreciation set up for both, the fixed charges on 11 surface lines would almost exactly equal that of the subway, which would be $850,000 per route mile per year.

The operating cost of the rapid-transit system per car mile is less than that of the surface line, and very much less per passenger handled. While it is impossible for either the privately operated or municipal subways to show an adequate return on the investment on a five-cent fare, and some of the surface rail and bus systems appear to be doing so, the conditions are not comparable.

The average rider on the surface travels not over two or three miles. The average subway ride is at least four times as long. If the surface lines had to carry their passengers the same distances as do the subway trains, instead of picking up a series of overlapping loads, their revenue per car mile or bus mile would decrease in inverse ratio to the longer ride and would fail to equal their out-of-pocket operating expense, whereas the subways operate for between 50 per cent and 60 per cent of their passenger revenue.

Aside from questions of operating economics, it would disrupt the business life of the community if those using public transport had to take two and one half times as long to get to work and return, which is about the ratio of schedule speeds on the surface to that of the subway.

Density of rush-hour traffic to and from the business areas is the final measuring stick that should govern the type of transportation service in every community. It is generally agreed that for our largest cities rapid-transit lines, subway or elevated, are an absolute necessity to the proper functioning of the community life. In addition, there is every economic justification for retaining and re-equipping a very considerable amount of surface rail transportation in these cities, and the rail service should be supplemented with trolley coaches and gas busses.

In the larger cities which are functioning without rapid transit facilities, it would appear that the modern rail car is still the most suitable vehicle for the heaviest traffic routes, but many existing rail lines should be changed to trolley coach operation. In many smaller communities, even up to perhaps 500,000 population, it is probably good engineering economics to gradually discard the rails and supplant them with trolley coaches and gas busses.

In all cities large enough to require mass transportation, it appears certain that electrically propelled vehicles, whether rail cars or trolley coaches, should be used for the great bulk of the service, having the ability to provide a faster, safer, more comfortable, and more economical form of passenger transportation than any other form now used in public service.

Transactions

Papers and Discussions Comprising Pages 61–114 of the 1938 Volume

The PCC Street Car

By C. F. HIRSHFELD
FELLOW AIEE

Synopsis: This car is the result of a collective effort to modernize and improve the street car. Its development was preceded by extensive investigation directed toward determining the characteristics of conventional cars and the ways in which and extents to which these should be modified to approach the ideals of street-railway executives and of the riding public, respectively. Car and equipment designs were then produced. These represent the best technical approach to these ideals which could be reached within the economic limitations which exist. The car has been made more agile, has been given better appearance and better performance in many respects which affect the passenger. In spite of the addition of equipment not used in the older cars and of many refinements of design it is obtainable at a price which appears to meet the economic requirements. Over 500 of these new vehicles are already in use in seven cities of this country.

THE VEHICLE which has become known as the PCC car is the product of several years of intensive research and development. The effort was initiated and sponsored by executives of leading street-railway companies. They realized the extent to which basic improvements in street cars had lagged behind the development of other vehicles available for both private and public transportation, and the undesirable effect this was having upon street-railway revenues. They believed that street cars must continue in use on certain routes and under certain conditions but they realized that the conventional street car fell far short of requirements.

These executives formed Electric Railway Presidents' Conference Committee as an instrumentality through which a modernized car might be developed. Abbreviation reduced this lengthy name to Presidents' Conference Committee and ultimately to PCC.

The assignment given the engineering staff of PCC was to determine whether the street car could be improved radically and, if so, how. One of its first endeavors was the determination of what were considered the faults in, and shortcomings of the conventional cars; and the characteristics which it was thought an ideally perfect car should possess. In this part of the investigation street-car operators and street-car users were consulted. In fact, interviews were also had with individuals who might have been passengers but were not.

One result of this investigation was the enumeration of a number of objectives of physical character. The principal ones were:

1. Great agility. This means ability to maintain high schedule speed in the face of frequent stops.
2. Modern appearance.
3. Low noise level, both inside and outside the car.
4. Good riding quality. This refers to the absence of high-frequency vibrations, the absence of repetitive low-frequency movements of objectionable sorts, and the absence of jerks or jolts.
5. Good ventilation.
6. Good illumination.
7. Minimum wear and tear of road bed.

Another result of the investigation was an enumeration of certain economic factors within the limitations of which the desired physical characteristics had to be obtained. These economic factors were:

1. Low first cost.
2. Low operating cost.
3. Low maintenance expense.

It is interesting to note that, as in the case of many of the older industries, little factual information of a technical character was available with respect to the performance of conventional equipment. The performance of representative cars in different respects had to be determined in order to establish what may be called points of departure. Frequently it was even necessary to develop instruments and test methods. Outstanding examples are furnished by the problems presented in attacking such important factors as riding quality and noise level. In a few cases it was found desirable to experiment on human beings to determine certain characteristics as, for example, their tolerances for different kinds of motion.

In the later design of new equipment the ideals determined by these early investigations served as the goals to be approached as nearly as technical ability and economic considerations permitted. An account of the methods adopted and, to some extent, the degree of success achieved forms the bulk of this paper.

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1. For all numbered references, see list at end of paper.

Great Agility

It is well known that the schedule speed attainable with street cars operating with frequent stops is determined almost entirely by the number of stops, the average length of stop, and the speed of starting and of stopping. The maximum attainable speed is of little consequence except in the case of long, uninterrupted runs.

The number of stops is a function of the passenger capacity of the car and the characteristics of the route on which it is operating. Once the size of car is determined, the designer has practically no control over the number of stops. The designer can however control the length of stop to a limited extent. For example, ease of entering and of leaving the car naturally tend to speed up passenger movement and thus to decrease the length of stop required to load or unload a given number of passengers.

This has been recognized in this case. Steps have been made to approach the proportions used in houses and office buildings to the extent that certain limiting conditions permitted. Effective illumination has been provided for the stepwells and the adjacent street area so as to facilitate mounting and demounting. Moreover, the illumination is so arranged as not to produce glare in the eyes of the moving passengers. The flow of passengers into and out of cars was studied and the PCC design provides as far as possible for natural flow, that is movement along the lines most naturally followed by the passenger. The seating arrangement is such as to provide the maximum practicable amount of open floor space in the front half of the car so as to permit ready movement toward the rear and ready access to the central exit doors. Stanchions and handrails are so arranged that there shall always be a handhold of some sort within easy reach of any passenger so as to encourage passenger movement while the car is in motion. Moreover, the handholds are so arranged that they afford a convenient hold for persons of all heights. Every effort was made to shorten the time of stops by these and similar methods. However, at best, the possible improvement of schedule speed by such methods is decidedly limited.

The greatest possibilities lie in increased speed of starting and stopping. Anyone who has watched the conventional street car during its slow and deliberate start will have observed the way in which the more agile automotive vehicles glide ahead of it, pre-empt its track and hold it down to a sedate but unacceptable rate of progress. Anyone who has watched the operation of the car in traffic will have observed how the operator is continuously throwing off power and applying his brakes in anticipation of a possible collision or the approach to an intersection at which he must stop. If the street car is to make reasonably high schedule speeds under modern conditions it must be capable of starting and stopping at rates comparing favorably with those of automotive traffic.

All this is well-nigh axiomatic. But a very vital question presents itself when one has arrived at this point. How rapidly can a standing human being be put into motion or brought to rest without excessive danger of accident? When this work was undertaken no one seemed to know the answer. It was decided to determine the tolerance of standing human beings for accelerating forces.

The results of this investigation have been published elsewhere.[1] Suffice it to record here that experiments were performed on standing passengers who were not holding onto any form of support. It was found they could tolerate the forces required to take them from a state of rest to an acceleration of 4.75 miles an hour per second in one second and to maintain the higher rate for two seconds or more. It was necessary only that the force be steadily applied; that is, there may be no marked and sudden variation in force during the entire process.

Tests on conventional cars showed that the forces applied to the passengers during acceleration fell far short of meeting this requirement, even when the automatic types of control were used. A variation of 50 to 100 per cent in very short time periods was not at all uncommon.

A performance specification was prepared which called for a constant increase of acceleration from zero to 4.75 miles an hour per second in one second, the maintenance of the higher value for two seconds and the maximum practicable approach to constant power input thereafter. After some experience this was modified to permit a lower rate of increase for a very short time at the start of the accelerating process. It was found that this arrangement was more acceptable to the passengers.

Equipment has been produced which approximates this performance specification very closely. It is now in use on over 500 cars in regular service in seven different cities and appears to produce results acceptable to the passengers. Certainly the car is much better able to take and hold its place in a stream of traffic.

With the starting process settled, there remained the method to be used for stopping. Experience with experimental cars showed there was no value in quick starting ability unless equal or greater stopping ability were provided. An operator would not avail himself of the ability to move fast unless certain that he could stop sufficiently quickly to avoid a collision with vehicles or pedestrians.

The maximum braking rate attainable with wheel to rail adhesion is well known and was not found adequate. Consequently magnetic track brakes were included in the braking equipment. The braking force produced by these devices is obviously independent of the coefficient of adhesion between wheels and rails and may be made additive to braking produced by the wheels.

The car is equipped with three different braking systems. These are: dynamic brakes dependent upon the use of the motors as generators; air-operated wheel-tread brakes; and magnetic track brakes. A service stop is normally made with the dynamic brakes supplemented by the tread brake as the dynamic brake "fades." At any time the operator can bring into use the track brake to increase the braking effect.

Normal or service braking is almost the reverse of the starting sequence. The deceleration increases at a constant rate to a desired value. After that it is maintained constant for the desired period and finally is decreased at a constant rate to zero value as the car comes to rest. The maximum deceleration attainable is between 8 and 9 miles an hour per second, depending upon rail condition and other variables. This has proved sufficiently high to yield safe operation and that feeling of security on the part of the operator which is necessary to the attainment of high schedule speed.

Acceleration and braking are produced by foot pedal operation as in an automobile. The operator need not know how the pedals operate the control equipment. He need only know that further depression of either one of them produces more of the effect which that one controls, and that too sudden application or release of pressure will produce uncomfortable jolts. The mechanism is capable of giving smooth performance if properly maintained. The necessary manipulation is simple and easily learned.

The balancing speed of the car is about 40 miles per hour. While of little significance in congested urban traffic, this speed is of value in the outlying districts where it can be used.

Modern Appearance

The airplane and the automobile have given the public certain ideas with respect to the appearance of an up-to-date vehicle. They have created what may be called a style. In the light of this style the conventional street car has a decidedly antiquated appearance and the public attributes antediluvian characteristics. It is obviously desirable that a modernized car should appear as such to the public which is expected to accept and patronize it.

The car has been given automotive appearance with respect to the major lines and all obvious fittings and decoration. Front and rear vestibule hoods are formed of metal as in the case of the automobile, and to similar lines. The letterboard has been corrugated to break its flat appearance and to produce an idea of motion. It runs by easy curves into the roof structure, just as the corresponding part does in the automobile. The windshield and the vestibule corner posts are enlarged versions of good automotive practice. The over-all height of the car has been materially decreased and a suggestion of "streamlining" has been introduced. The windows are arranged to produce group effects and they have rounded corners.

It is important to note that the matter of appearance was not treated separately. Innovations have been made with an eye to reduction in weight and to the production of a vehicle mechanically better adapted to its task. There should therefore be some lasting value in the changed appearance.

Low Noise Level

The greater part of the noise made by conventional street cars originates at the wheel-rail contact and at metal-to-metal contacts in the trucks. These noises are not only broadcasted at the points of origin but are also transmitted through the metal of the truck to the car body which in turn serves as a huge sounding board.

The general principles adopted for the suppression of noise may be described as maximum practicable suppression at the source and the minimum practicable transmission from that source. The steel tire was retained of necessity. But it is supported in rubber within the wheel in such a way that noise generated at the contact with the rail is absorbed in that rubber to the maximum practicable extent. The truck is so designed as to substitute rubber articulation for metal-to-metal contacts. Thus wear and accumulation of lost motion, with resultant noise, are prevented and rubber is used to break the otherwise continuous metal paths through which the sounds would be transmitted. The use of rubber in this way has been carried to the extent of eliminating steel car springs completely and using specially designed rubber springs instead.

These and other departures and refinements have both materially reduced the noise level and made the remaining noise of more acceptable quality.

Good Riding Quality

When this work was undertaken there was little information available with respect to the tolerance of human beings for vibrations of different magnitudes and frequencies, and oriented in different directions. An attempt was made to obtain sufficient information to serve as a guide in the design of a better car. The results have been published[2–4] and need not be detailed here.

Two types of vibration or disturbance came up for consideration. These may be called high frequency and low frequency although there is no sharp demarcation. The high-frequency disturbances are practically all in the audible range; that is above 20 to 25 per second. The low-frequency disturbances are of the order of 0.2 to 5 per second.

Space does not permit a lengthy explanation nor a detailed account of the methods used to bring about acceptable conditions. The high-frequency vibrations were almost completely eliminated by abandoning the use of the conventional leaf spring and substituting the rubber spring referred to above; and by designing certain parts of the structure stiffer than had been customary. The lower-frequency vibrations and disturbances of an objectionable sort were minimized by the design of the springing system and by a radically new method of suspending the axle in the truck.

The results obtained have been checked by adequate instruments throughout the entire development. There is therefore no question regarding the extent of the improvement. Recording accelerometers adapted to measure accelerations in the three principal directions show the floor of this car to vibrate very little, through very small amplitudes, and at very low frequencies. Such movements as do occur are characterized by low accelerations so that the record is a wavy instead of a jagged line. The conventional cars give very jagged records, showing numerous high and low frequencies of large amplitude superposed so as to produce "beats" which further aggravate the situation.

Closely associated with good riding quality is reasonable freedom from jolts caused by operation of motor control and of brakes. This has been referred to above. The equipment provided is such that a moderately careful operator can produce remarkably smooth operation without having to possess exceptional skill.

Good Ventilation

The ventilating and heating arrangements are combined into one system. Motor and brake control resistors are enclosed in a compartment under the center of the car where they are protected from the weather. A motor-driven fan blows over these resistors the quantity of air required to maintain them at a safely low operating temperature. During the heating season more or less of this air, as required, is blown into the car after being warmed by passing over the resistors. What is not needed to maintain the car temperature is wasted through thermostatically controlled dampers.

The air handled by the fan is drawn from the car interior through ducts which form part of the car structure. This air enters the car by different routes. Part of it enters by leakage around doors and at other places. Part of it enters through a roof ventilator so designed that the quantity passed increases with car speed. During the heating season part of it is blown in by the fan as above described and is in reality recirculated.

The total quantity of air passing through the car interior varies with conditions. The minimum aimed at is 1,200 cubic feet per minute. This is, in fact, a very generous supply when considered in terms of building ventilation.

Good Illumination

Illuminating engineers have consistently urged greater intensity of artificial illumination in the interest of less eye fatigue and greater health. Vehicle illumination has commonly been of the order of 2 to 5 foot candles on the passenger's reading plane. Office illumination has seldom been greater than 10 foot candles on the table or desk top although recent installations have shown a tendency toward at least doubling this figure.

Recognizing that the public of this country reads extensively while riding and that at best there will be a certain amount of uncontrollable movement of the printed surface with respect to the eye, it seems reasonable to conclude that a high degree of illumination should be provided in mass transportation vehicles. A value of 15 foot candles on the reading plane of the seated passenger was chosen in this case, with provision for raising it to 20 if later found desirable.

Two difficulties are encountered when attempting a high intensity of illumination in a street car. First, the ceiling is necessarily low and it is difficult to install thereon or therein sources of illumination capable of giving the desired standard of lighting without producing at the same time most objectionable and nerve racking glare. This difficulty has been at least partly surmounted by the development of new types of fixtures and methods. Completely indirect lighting is capable of producing a technically satisfactory result but it is undesirably expensive both as to first cost and as to operation. Lens types and louver types of lighting fixtures have thus far offered the most satisfactory solutions.

The second difficulty arises from the fact that the human eye adjusts itself rather slowly when one goes from an area of high illumination intensity to one of low intensity. Every passenger must ultimately alight from the car. If this involves stepping into a poorly illuminated street from a brightly illuminated car the passenger is temporarily almost incapable of seeing sufficiently clearly to guard against accident. The intensity chosen, combined with a reasonably high illumination of the street surface outside the exit door by means of car lighting, appears to be within safe limits.

Minimum Wear and Tear of Road Bed

The action of a rolling vehicle upon a road bed is not yet completely understood in a technical sense. It is known that the wear and tear increases with increasing weight of the unsprung parts and with increasing weight of the vehicle, all other things being equal. It is also known that it increases at a rapid rate if the assembly of masses and springs happens to be resonant to a frequency that can be imposed by the road bed, as for example rail joints or pavement joints. It is also known that violent movements of the vehicle, such as "nosing" and "galloping" tend to rapid destruction of the road bed.

In the present case all these facts were taken into consideration in the design of the vehicle. The completely unsprung weight consists of the wheel tread combined with part of the disk of the wheel whereas in the conventional car it consists of the entire axle assembly and a large fraction of the motor. The weight of the trucks, including the rather heavy magnetic track brakes, is somewhat less than that of conventional trucks without such brakes. The weight of the complete vehicle is 33,000 pounds against figures of the order of 38,000 to 45,000 for the later cars of conventional design. It is believed that refinement of design may bring the weight to a figure nearer 30,000 pounds. The present weight is achieved with steel construction. If the economics of the situation should ultimately show that the extensive use of lightweight alloys can be justified, the total weight could be reduced drastically; in fact a reduction of two to three tons is not inconceivable.

Resonance and violent movements have been minimized by careful attention to the dynamics of the assembly and by certain innovations in truck design, including the new suspension of the axle in the truck referred to above.

Economic Considerations

It has been stated that the technical improvements that have been reviewed briefly in the preceding paragraphs had to be achieved within certain economic limitations. Obviously a technically perfect car would be of no value to the industry if it did not also possess such characteristics as to make it economically usable. The following paragraphs are devoted to these economic factors.

Low First Cost

The street car is only one of several types of vehicle available for mass transportation. Each type has certain physical and economic characteristics which determine its proper place in a well-co-ordinated transportation system. The street railway is operated on and with structures which necessitate a considerable investment; fixed charges therefore are very significant in its economy. Its compensating advantage is that where traffic density is sufficiently high the unit cost of handling passengers is lower than in the case of any other form of surface transportation. Thus the economic field of the street car under given circumstances and in comparison with other public vehicles, such as busses, is circumscribed by the extent to which fixed charges can be limited. It follows that low first cost of vehicle is particularly important.

Much serious thought was given to the possible means of obtaining low first cost because it was known that a car which would give the desired performance would require more equipment and greater refinement of design than previously had been used in this field. That is to say, the problem was to develop a much better car saleable at a lower price. Experience in other industries pointed to standardization as one possible means. Here, however, further difficulty was injected by the very real physical differences and the limitations which exist upon the street railway properties in various cities. It is only necessary to mention by way of illustration the different track gauges in use and the limitations on external contour which result from unchangeable clearance conditions on the individual properties.

This phase of the problem was attacked by standardizing parts and sub-assemblies which, within limits, could be assembled to produce the different vehicles required by different cities while retaining most of the economics of standardized production. Thus, the body between corner posts is a standardized assembly usable without change on nearly all properties in this country and Canada. The front and rear vestibules are each standardized and are usable on all properties. A car made of the standardized body and these vestibules is usable on most properties. It is known as the "basic car." This has an over-all length of 46 feet.

A property requiring a shorter car obtains it by dropping out one window panel. This shortens the car by 30 inches. A property requiring a longer car obtains it by putting a filler piece between one vestibule and the adjacent end of the car body. Such modifications of the basic car are already in use.

The standard arrangement is front entrance, center exit. It was known that other arrangements would be required on certain properties, including an additional rear exit door in one case. The structure is so designed as to make such modifications possible at minimum cost.

The truck presented a more difficult problem than did the car body. Track gauges in use vary from three feet six inches to five feet four and one-half inches. The first attempts to produce a truck design embodying the principles which had been found necessary, and still easily modifiable to fit all track gauges, were not completely successful. A design was evolved which could be used with very minor modifications on standard and wide gauges. Later a second and more flexible design was developed. This is now in use on one narrow gauge property. It can be modified very simply to adapt it to any track gauge.

As the solution now stands, the same major parts can be used in trucks of any gauge. Certain minor modifications are required. For example, the lengths of axles and of axle housings must vary with the gauge. However, the variations necessary in different parts are of such character as to entail a minimum of expense.

The method of standardization adopted has worked well in practice. Cars have been purchased at prices which make them economically usable in spite of the addition of many items and of the refined construction required to obtain the improved performance aimed at.

Low Operating Cost

The two principal factors in operating cost are platform labor and power. Probably the next most important factor is the cost of accidents; if that be included under this heading.

Provision has been made for reducing platform labor cost to a minimum through two factors, namely, providing for increased schedule speed and by designing the car for one-man operation. This does not mean that it was merely arranged for such operation; it was designed to make it possible for one man to perform all required functions with the maximum of convenience and the minimum of fatigue. Included in these provisions are foot operation of the car with respect to power and brakes; a comfortable, well placed and adequately adjustable operator's seat; a well ventilated and properly warmed operator's position; a conveniently located gang switch controlling all auxiliary functions, and numerous other details.

The power consumption per car mile is greater than that of the conventional car. The greater agility demanded brings this about as an unavoidable consequence. In addition, the requirement of maximum smoothness during acceleration further increased the power consumption through the elimination of the commonly used series-parallel type of control. The philosophy back of this step is that the performance of the car must be made acceptable to the public. If such performance requires increased power consumption the car must carry this burden. Should it prove economically unable to do so it no longer has any place on the street.

The increased power consumption is, however, offset more or less perfectly by the use of control resistor heat for car heating. In this way the annual peak demand is relatively reduced and, under the form of contract on which most street railways buy power, its cost is correspondingly reduced. It remains for experience to show to what extent this balances the increased power consumption.

It is still too early to draw conclusions with respect to accident hazards. The cars now in use are comparatively new instruments with characteristics quite different from those of their predecessors, but operated by men who were trained in the use of the older equipment. It is however certain that the use of the magnetic track brake has made stopping much more independent of the condition of the rail and has thus reduced one well-recognized hazard.

Low Maintenance Expense

It is almost axiomatic that "wear and tear" tends to increase with speed. However, it is not necessary that they do so, in an absolute sense. One may so design that maintenance is lower at high speed than with other designs at low speed. This has been attempted in this case.

The body of the car is a completely welded structure so that it acts as a unit in contrast to riveted structures which sooner or later act as a rather loosely knit assemblage of parts. Collision experience had thus far appears to prove that this body suffers less damage and is more easily repaired than was the case with the older type of structure.

Moreover, the body is made of an assemblage of standardized and interchangeable parts, just as is an automobile. Therefore, replacement parts may be both relatively cheap and relatively cheaply installed.

Most of the electric and other moving equipment is enclosed in ventilated compartments so that it is protected from the weather and given the best chance for uninterrupted operation. All this equipment is standardized and arranged for easy removal and replacement by similar parts. To a great extent the mounting dimensions of competitive makes of equipment are standardized. It follows that in many respects maintenance can be performed by replacement of a piece of equipment with an equivalent piece so that the primary investment can be returned to service immediately. The equipment which has been removed can be transported to a bench arranged for the easy and cheap performance of the necessary maintenance operations.

Propulsion motors are supplied with ventilating air which is taken from outside the sides or the car, carried through ducts within the car-body bolster structure, and delivered to the motors through bellows connections. In this way much of the dirt that ordinarily finds its way into street-car motors is excluded. The maintenance requirements should be correspondingly reduced.

The trucks of street cars are generally responsible for high maintenance costs if they are adequately maintained. The new trucks were designed to reduce maintenance requirements and to simplify the performance of such maintenance as is required. It has already been indicated that relatively moving metal-to-metal contacts have been avoided in so far as practicable. Where they are absolutely essential, as in journal bearings and gears, provision is made for flooded lubrication and the proportions are calculated for a life of 750,000 miles. In many cases necessary articulations are made by means of rubber so arranged that distortion of the rubber within very conservative limits permits the necessary relative movements of metal parts. The principle followed in the use of rubber is to have all parts with respect to which relative motion is required literally float in rubber.

The trucks are so designed that they consist of an assemblage of standardized and interchangeable parts, readily removable from the assembly as integral units. The favorable effect upon maintenance is obvious.

Finally, as already indicated, the trucks are mounted on resilient wheels. Experiment in the laboratory and on regular street-railway equipment in the street showed that this type of wheel reduced tremendously the destructive forces to which the parts of the truck are subjected. In spite of this fact, all truck parts have been designed for operation on conventional solid wheels, so that the resultant high factor of safety should be effective in minimizing maintenance expense.

Such figures as are available to the author indicate that in spite of all the radically new features in car body and trucks and in spite of all the unforeseen and unforeseeable errors that enter into the design, manufacture and use of new equipment of this sort, the maintenance expense on these cars is now of the same order of magnitude as that of the older cars in spite of their higher schedule speeds and in spite of the lack of experience in handling them on the part of both operating and maintenance personnel. This gives ground for the belief that when initial errors in design and fabrication are eliminated, and when the personnel involved becomes more familiar with this equipment, the maintenance expense will in fact be considerably lower than that characteristic of the older forms of rolling stock.

Such, in brief, is the history and status of development of the PCC car. It certainly represents both a major technical and economic advance over the conventional vehicle previously available. Even so, it must be considered only one more link in a practically endless chain of improvement. The heads of those who produced this product are already filled with visions of the further steps that might be taken. The present product is in reality a modernization and refinement of the older vehicle; radical in a few respects but still adhering fairly closely to the conventional. There is good reason for believing that much more radical changes are not only possible but would be economically valuable.

To the author, this development is interesting chiefly because it demonstrates the dollar value of the research method in an old and apparently completely developed line of endeavor. Now that the door to new designs has been opened, lengthy vistas, extending far into the future and apparently filled with promise, have come into view.

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A New A-C Network Analyzer

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Introduction

WHEN POWER systems were relatively small and simple, frequently comprising only one generating station with a radial distribution system, there was little need to study the effect of a proposed addition or change on an existing system. The growth and in recent years the interconnection of power systems have brought with them an increased quality of electric service and divers new devices for maintaining that service. In a power system of the size and complexity of many of those now in operation, many of the component parts inherently have the ability to profoundly affect the successful operation of the system. Consequently, it has become necessary for engineers to study their systems much more critically and to know a great deal more about them than heretofore. Fortunately, the technical background for such critical studies has kept pace with the increase in size and complexity of power systems. However, the calculations which constitute a large part of the work of making such a critical study, when carried out by long hand methods are generally laborious—frequently, sufficiently laborious to greatly curtail the scope of the study and at times to prevent the study being made altogether.

To simplify and shorten the work of making calculations of this sort, the a-c network analyzer has been developed. It is a tool which in the hands of a competent engineer becomes a very valuable aid in analyzing the performance of systems and apparatus. Moreover, a much more complete analysis of a power system and the interrelated performance of its component parts may be obtained from the analyzer data than can be gathered from actual system data and operating reports, which must of necessity be in some degree incomplete.

The analyzer affords a quick and effective means for studying major system disturbances in order to check and correlate available field observations, to determine what probably occurred, and to compare suggested remedies. It is useful also for observing in "slow motion" the sequence of events during abnormal system operation. Periodic checks with it of normal system operation and of operating instructions frequently show important changes brought about by the shift and growth of loads. Furthermore such checks often afford explanations for unusual observed operating phenomena. The comprehensiveness of the picture secured with the help of the analyzer of all the many factors which enter into the solution of a problem and which must be accurately weighed in fashioning its solution has created a feeling among those who have used the analyzer that all changes and additions to power systems involving major expenditures could profitably be critically studied with it.

From the historical point of view some of the first attempts to study power system problems were made with miniature three-phase systems using laboratory equipment,[1] some employing rotating machines as large as 600 kva at 23,000 volts[5] for the determination of stability and power limits. A general purpose three-phase miniature a-c transmission system for the practical solution of network and transmission problems employing 3.75 kva rotating generators was constructed and extensively used in the General Electric Company.[3,4] In all of these early arrangements rotating generators of appreciable power were used. Later, however, the method of symmetrical-component analysis of unbalanced three-phase systems suggested the use of single-phase artificial representations of such systems. The representation of generators by means of static phase shifting transformers and the use of transformer equivalent circuits was described by Messrs. H. H. Spencer and H. L. Hazen[6]. By applying these principles, the MIT network analyzer[9] was built jointly by the General Electric Company and the Massachusetts Institute of Technology. Another a-c calculating board of interesting design was also built and described by the Westinghouse Electric and Manufacturing Company.[10]

Design Fundamentals

Experience gained through the operation of the earlier analyzers showed that refinements in the general usability, degree of accuracy and reduction of size, and weight are desirable.

Usability may be considered from several standpoints. For example, in setting up the network on the analyzer a suitable number of circuit units should be available to adequately represent any power system. System quantities should be easily converted into analyzer quantities and vice versa. The adjustment of analyzer circuit units should be simple and connections of the units to form a network should be capable of being made with facility. The parts of the analyzer should be so arranged that visual checks of the connections and settings of the units can be readily made. It follows that all of these things apply equally well when adjusting an already formed network to a new set of conditions.

If the measuring system is to have maximum usability it should be such that data may be obtained from the analyzer as rapidly as it can be recorded, and that desired electrical quantities such as volts, amperes, watts, vars,

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1. For all numbered references, see list at end of paper.

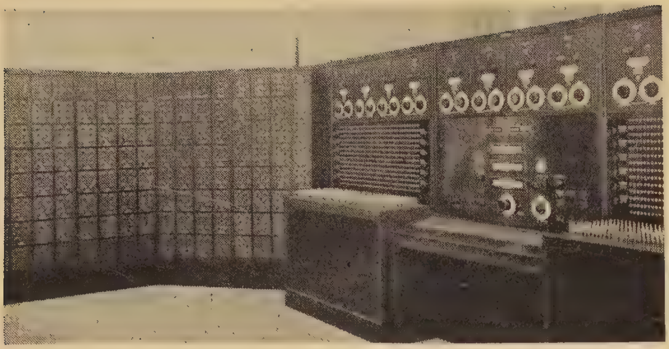

Figure 1. Network analyzer showing the general arrangement of cabinets

vector components of voltage and current as well as phase angles should be read directly. It must be easy to insert the measuring instruments in the network at the points desired and to read the instrument scales accurately and without eyestrain. The importance of obtaining correct data can hardly be overemphasized, as mistakes which arise either through faulty plugging and setting of units through improper reading of instruments or through fatigue, sometimes result in serious delays and unnecessary duplications of work.

A network analyzer should have a degree of accuracy at least equal to the accuracy of the constants of the systems which are to be reproduced in miniature. An even higher degree of accuracy is desirable in order that small differences in operating conditions and apparatus constants will produce the corresponding changes in associated network currents, voltages, and power flow. It is also desirable that a sufficient number of adjustable steps be provided on the circuit units that system constants may be set up with a good degree of accuracy. The instruments must have sufficiently low burdens that they will produce negligible changes in network currents and voltages. Moreover the departures of the analyzer units and instruments from their calibration should seldom be sufficiently large that correction of the measured results are necessary.

In view of the fact that the large number of circuit units generally occupy the greatest portion of the analyzer space, these units should be made small in order to reduce the analyzer size and weight. This can be achieved, as a preliminary design analysis showed, by using small network currents and voltages and by selecting an appropriate operating frequency. In this manner the power consumption is also minimized so that a small motor-generator set may be used. Furthermore, the over-all heat dissipation from the analyzer becomes small as is desired. In addition, standard high-quality low-cost switches, terminal plugs, etc., which, through years of use in radio and telephone fields have attained a high degree of durability and dependability, may be used.

The New A-C Network Analyzer

In the design of the analyzer described in this paper an effort was made to achieve all of the objectives outlined in the preceding section. In order to satisfy certain of these objectives many new developments were necessary, particularly the development of a new instrument system including amplifiers.

Before discussing in detail the essential design features and engineering problems it is perhaps well at this point to describe briefly the new analyzer recently placed in operation in the General Electric Company at Schenectady.

The general arrangement may be seen from figure 1 showing the center and one wing of the analyzer. It is assembled symmetrically with respect to the centrally located instrument and control cabinet. A circuit-connecting cabinet is situated on either side of this control cabinet and each wing is formed by four cabinets containing the adjustable circuit-element units. The distance from wing to wing is 26 feet and the depth is 11 feet. Power is supplied to the network through generator units placed in the upper part of the circuit-connecting cabinets and the instruments and control cabinet. This power is derived from a motor-generator set and phase balancer remotely located from, but controlled from the analyzer.

Each circuit unit terminates in a set of flexible cords and plugs on the connecting cabinets. By inserting these plugs in horizontally adjacent jacks of the vertical jack panel of these cabinets the circuit units may be connected together to form the desired network. The end jacks of each horizontal row of one jack panel are connected to the respective end jacks of the other jack panel, thus interconnecting them. The generator units are connected to rows of jacks located on the extreme ends of each jack panel.

Key switches are provided on the inclined panel of the instrument cabinet to connect any circuit unit or "jumper circuit" of the network to the instrument busses. Other switches for operating the instruments are provided on the vertical instrument panel so that the operator may

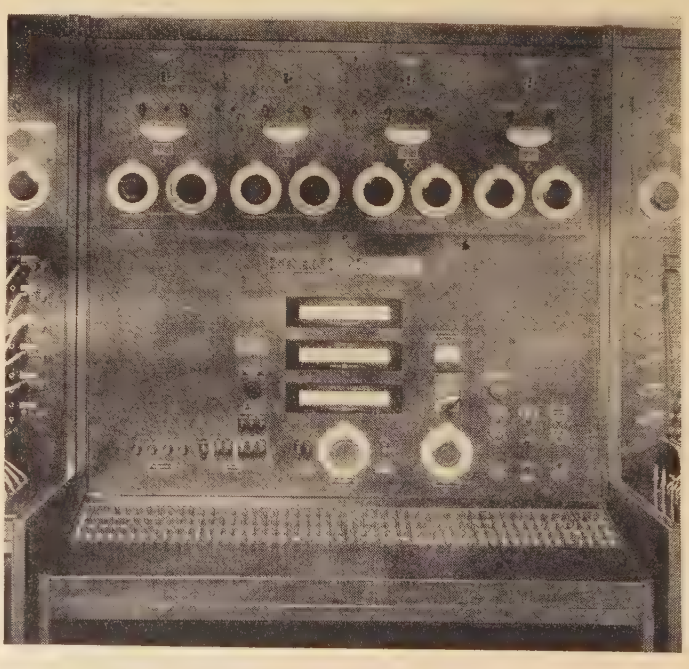

Figure 2. Central instrument and control panel showing generator units and instruments with their control switches

measure the magnitudes or vector components of voltage, current and power, and phase angles in any branch of a network without moving from in front of the instrument cabinet, a close view of which is shown in figure 2.

The master instruments consist of an ammeter, voltmeter, and wattmeter-varmeter. They have light-beam pointers in order to secure a short response time. The light beam pointers used in conjunction with eight-inch scales reduce eyestrain to a marked degree. In order that these instruments shall have very low burdens and so make an inappreciable change in the network currents, current and voltage amplifiers are used.

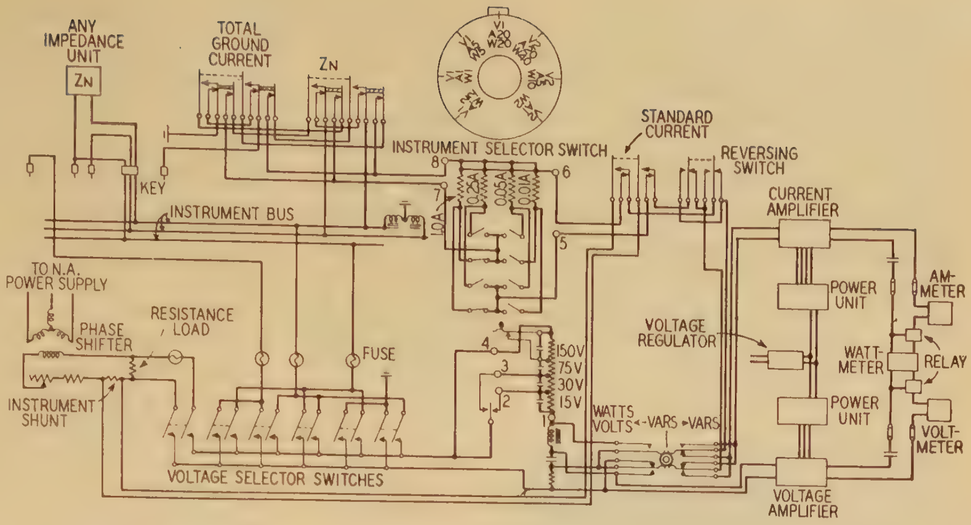

Figure 4. Schematic circuit diagram of the instrument system connections

The dials and scales of all of the analyzer circuit units and instruments are marked in per cent. With this marking the multipliers for changing system quantities into analyzer quantities and vice versa are simpler than they would be if the analyzer scales were marked in actual volts, amperes, and ohms. Furthermore, as a great many system calculations are made using percentage quantities, data for these systems may be frequently transferred directly to the analyzer. The nominal or 100 per cent voltage is 50 volts and the nominal or 100 per cent current is 50 milliamperes. Consequently 100 per cent ohms on the analyzer corresponds to 1,000 ohms.

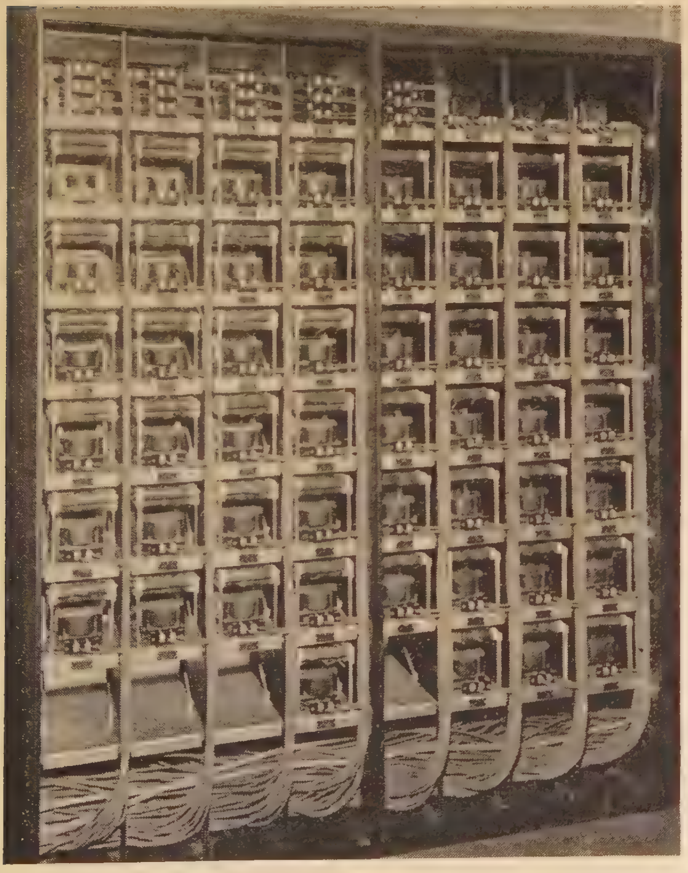

Figure 3. Rear view of two circuit-unit cabinets showing the wiring details

The wiring between sections of the analyzer is carried in the base of the cabinets as may be seen from figure 3, which shows a back view of the circuit-unit cabinets. The circuit units are mounted in individual compartments and may readily be removed for inspection.

All cabinets are of the unit type and might have been arranged in any other manner than that shown in figure 1 if the configuration of the room had required it.

The Instrument System

One of the most important parts of the network analyzer is the master-instrument group and its controls. The master instruments, the voltmeter, the ammeter and wattmeter-varmeter, are of the "light beam" type with eight-inch scales having 150, 100, and 150 divisions respectively. The "light beam" pointer is a luminous figure on the opalescent instrument scale consisting of a thin vertical line. These instruments were constructed from modified standard instrument elements by replacing the pointers with reflecting mirrors in the usual manner. Owing to the light-beam pointers and suitable moving system springs, the time of response of these instruments is a fraction of a second. The voltmeter and ammeter are of the moving-iron-vane type and the wattmeter-varmeter is a d-c milliammeter of the permanent-magnet moving-coil type whose d-c operating current is supplied by the wattmeter proper which is a sensitive torque balancing telemeter. In this telemeter-wattmeter a null method of measurement similar to that of the photo-electric recorder was used.[16] The a-c potential coils and the current coils of the instruments are connected in series so that all master instruments indicate simultaneously.

For the nominal analyzer voltage and current of 50 volts and 50 milliamperes, a maximum potential drop of 0.01 volts across current shunts and a potential current not exceeding 0.3 milliamperes were set as limits of instrument burden. Inasmuch as the master voltmeter and ammeter circuits require 100 milliamperes and 50 milliamperes for full scale deflections of the instruments, suitable amplifiers were developed to supply the instrument power—one for the potential circuit and the other for the current circuit. These amplifiers are of the stabilized feed-back type. By the use of this principle, the amount of gain is very nearly independent of plate voltage fluctuations and changes in tube characteristics over a wide range.

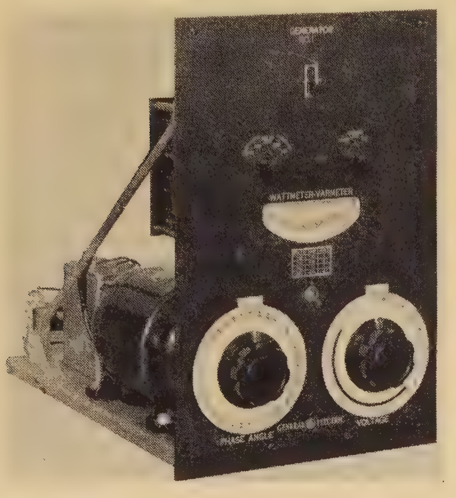

Figure 5. Generator unit

The accuracy of the amplifiers is further improved by a simple transformer-type checking circuit which automatically compares the amplifier input and output and introduces into the amplifier a voltage corresponding to any differential from the correct ratio of these two quantities, so that the amplification ratio is accurately maintained. The amplifiers have an accuracy of better than plus or minus 20 minutes in phase angle and plus or minus one-half per cent in magnitude. They are fully described in a paper by H. A. Thompson.[15]

A complete schematic circuit diagram showing the connections of the instruments, amplifiers, and the instrument switches is shown in figure 4. Referring to figure 2, the instrument-scale-selector switch, having seven positions corresponding to the most common voltage and current scales used, is installed just below the master instruments. By means of an auxiliary switch located on the right of the scale selector switch two additional low-voltage ranges are provided. On the left of the scale selector switch there are installed the watt-varmeter switch and the current-reversing switch.

By means of voltage switches, which are in the bottom row to the left of the master instruments, the voltages across any circuit unit or from either side of a circuit unit to ground, or from either side of a circuit unit to another point in the network, may be connected to the voltage amplifier. In addition, for measuring vector components of current, a reference voltage obtained from the instrument Selsyn (Selsyn is a registered trademark of the General Electric Company), which is below and to the right of the master instruments on the panel, may also be connected to the same amplifier. Three current switches are provided just above the voltage switches to connect the current amplifier through shunts to the ground bus or any circuit unit, or to the reference current circuit of the instrument Selsyn.

On the right side of the panel there are the start-stop push-button stations for the motor-generator set, the on-and-off push-button stations for the power-supply contactor on the motor-generator set control panel and for the amplifier-power and instrument-light switch. There is also a switch for changing taps on the autotransformer in the power supply circuit in order to obtain a convenient reduction in the voltages of all generator units simultaneously to 50 or 25 per cent voltage when faults are applied to the network. A miniature type voltmeter is supplied to indicate the analyzer supply voltage. A rheostat is provided to adjust the voltage held by the voltage regulator associated with the motor-generator set. To the left of the master instruments a second rheostat is provided to adjust the voltage and current of the instrument Selsyn.

The potential shunt or voltage divider and the current shunts for the master instruments shown in figure 4 are mounted in the scale-selector-switch housing. Because of the high impedance of the voltage divider, the capacity coupling to ground and to adjacent electrical circuits of the divider elements introduces currents which cause phase-angle shifts. It is necessary to have very close adjustment of phase angles to measure power at low power factors with the degree of accuracy sometimes required in stability studies when large machines are involved. In order to control these stray-capacity effects, adjustable trimmer capacitors have been connected across the resistance parts of the divider to equalize the phase-angle shifts on all taps. The effects of the capacity to ground have been made inappreciable by proper shielding of the divider, shunt leads and switches. Inasmuch as the voltage divider now has a permanent and constant leading phase-angle shift the current shunts have been wound inductively and made adjustable in inductance in order that the voltage drop of each shunt will have the proper phase position with respect to the input voltage of the potential amplifier for correct measurement of power at power factors approaching zero.

In the diagram of figure 4 only a typical circuit unit and corresponding key switch is shown; there are 300 key switches in the analyzer, one for each circuit.

The over-all accuracy of the master voltmeter and ammeter systems is within plus or minus 0.5 per cent of full

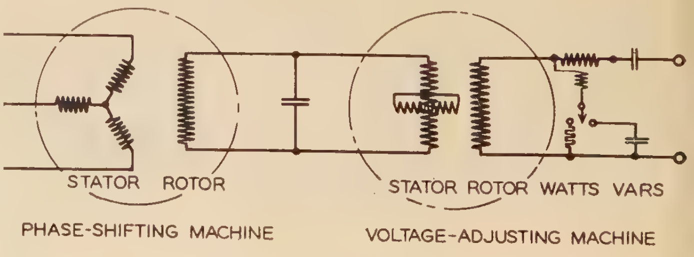

Figure 6. Schematic circuit diagram of generator unit

scale. The wattmeter-varmeter has the same accuracy when the phase angle between the current and voltage is not large. For very low power-factor measurements the most frequently used instrument connection has been carefully adjusted as described above to give accurate measurements of watts and vars at phase angles between the voltage and current approaching 90 degrees. For all other instrument connections there is a maximum instrument system phase angle displacement of the order of one degree.

The Analyzer Generator Units

Referring to figure 1, 12 adjustable single-phase power-source or generator units are installed in suitable compartments located at the top of the two plugging cabinets and the central instrument cabinet. These units are completely self-contained and may be inserted or removed from their compartments from the front. A photograph of one of these units is shown in figure 5.

Each generator unit consists of two power Selsyns, one having a three-phase stator and single-phase rotor for phase-angle control, the other having a two-phase stator and a single-phase rotor for voltage control. A schematic connection diagram is shown in figure 6. The three-phase stator winding of the phase shifting Selsyn is excited at 220 volts and 480 cycles through an autotransformer from the main power supply, the motor-generator set. The phase angle of the induced voltage in the single-phase rotor winding depends on the rotor angle. The rotor-output voltage is applied to one of the quarter-phase stator windings of the voltage-adjusting Selsyn. By turning the single-phase rotor of this machine the voltage may be varied from zero to a maximum at an essentially constant phase angle. As shown in the circuit diagram of figure 6, capacitors were used to compensate for magnetizing current and the equivalent single-phase reactance of the unit.

The full-load (100 per cent current) voltage regulation of the unit is approximately 2 per cent at unity power factor and essentially zero at zero power factor. The phase-angle shift for a corresponding change of current at zero power factor is approximately one degree at zero power factor and approximately zero at unity power factor. Because of this close regulation, a calibrated voltage dial was supplied with the voltage regulator instead of a voltmeter. By means of a gear transmission, the 90-degree mechanical rotor angle, from zero to full voltage, is magnified to an angle of approximately 300 degrees on the voltage dial, making the setting of the voltage more convenient.

The only direct-reading instrument mounted on the panel of this unit is a wattmeter-varmeter for measuring or adjusting the active and reactive voltampere output. This instrument has 150 per cent and 300 per cent voltage ranges and 100 per cent and 400 per cent current ranges. Switches are provided for changing scale multipliers and for short-circuiting the current coil when the generator-unit current exceeds 400 per cent. A switch is also supplied to disconnect the generator unit from the power supply.

Table I. Voltage-Wave-Shape Analysis of Analyzer Power Sources

Harmonic	Frequency (Cycles)	Voltage Components					
		Volts	Per Cent	Volts	Per Cent	Volts	Per Cent
At no load							
1	480	50.00	100.00	100.00	100.00	125.00	100.00
3	1440	0.13	0.26	0.5	0.5	0.66	0.525
5	2400	0.65	1.3	1.26	1.26	1.53	1.22
7	3360	0.028	0.056	0.057	0.057	0.068	0.054
With 0.25 ampere (500 per cent) at 70 per cent power factor							
1	480	50.00	100.00			125.00	100.00
3	1440	0.11	0.22			0.73	0.58
5	2400	0.62	1.24			1.68	1.34
7	3360	0.0275	0.055			0.066	0.053

In the design of the power supply motor-generator set and also of the analyzer generator units themselves, care was exercised to keep harmonics in the voltage to a minimum. With the complete analyzer equipment installed a voltage-wave-shape analysis was made at the output terminals of the generator units. The results are shown in table I.

The fifth-harmonic voltage is the largest but it does not exceed 1.4 per cent. Thus the analyzer generator-unit output voltage is very nearly sinusoidal.

The Circuit Units

For the representation of power systems by means of artificial miniature equivalent circuits there are generally used, in addition to generator units, adjustable resistors, reactors, capacitors, autotransformers, and mutual reactors. These may be combined into groups to form network branches. In the new analyzer there are five different types of circuit units as follows:

(*a*). Line-impedance units. These consist of adjustable resistors and reactors connected in series and are intended for representing lines or other circuits of relatively small impedance.

(*b*). Load-impedance units. These units also consist of adjustable resistors and reactors which may be connected either in series or in parallel. They differ from the line-impedance units in that their impedances are much higher.

(*c*). Capacitor units. The adjustable capacitors of these units are used to represent line capacity, and frequently to represent synchronous condensers as well as negative reactance such as occur in equivalent transformer circuits.

(*d*). Autotransformer units. The autotransformers are used to step up or down the voltage at points in the network.

(*e*). Mutual-transformer units. By means of these units magnetic coupling between circuits may be simulated. They are 1:1 ratio transformers. The desired degree of mutual coupling is obtained by connecting across the secondary a suitable impedance.

All units, with the exception of the last one which is not adjustable in itself, are mounted on individual 7- by 16-inch metal bases with calibrated front panels attached. These mounted units fit interchangeably into the compartments of the circuit-unit cabinets. The mutual-transformer units are mounted on racks back of the connection cabinet jack panels. Figure 7 shows a photograph of a line-impedance unit and a load-impedance unit while figure 8 shows a capacitor-unit and an autotransformer

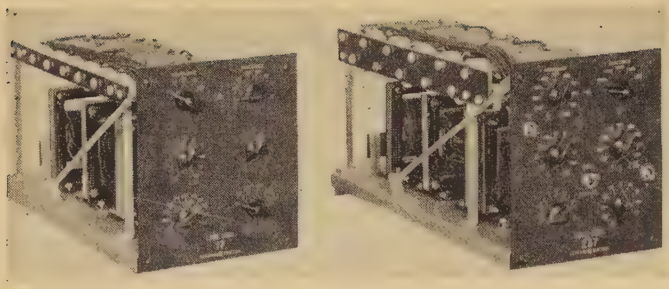

Figure 7. Line and load-impedance units

unit. An individual mutual-reactor unit is shown in figure 9.

In determining the proper number and the kind of units for the analyzer a great many systems were inspected and their constants tabulated. Studies which have been made on other analyzers were thoroughly reviewed. The constants of synchronous machines, transformers, and the like, were examined in order that the analyzer units would cover adequately the necessary ranges of impedance and fineness of steps. The following table shows the number and range of circuit units in the new network analyzer.

Table II. Number and Range of Circuit Units

Units	Number	Per Cent Range	Steps
Line-impedance units (series $R + jX$)	150	R 0–51 per cent	Continuous
		X 0–81 per cent	0.2 per cent
Load-impedance units	50	R 0–1,610 per cent	Continuous
(series or parallel $R + jX$)		X 0–1,605 per cent	5 per cent
Capacitor units (susceptance)	30	0–100 per cent	1 per cent
Autotransformer units	12	± 15 per cent.*	1 per cent
Mutual-reactor units	15		

* Values expressed in per cent of primary voltage.

The resistance and reactance part of each line-impedance unit and load-impedance unit is individually rated at a maximum of 62.5 volts (125 per cent nominal voltage) or 250 milliamperes (500 per cent nominal current) whichever is the limiting factor. Each capacitor of the capacitor units is rated at a maximum of 62.5 volts (125 per cent nominal voltage). The tapped resistances and capacitors have an accuracy of plus or minus one per cent on all taps. Small variable resistors have an accuracy of plus or minus three per cent. All reactors have an accuracy of plus or minus one per cent at a specified current and a change of reactance less than plus or minus two per cent over the full current range at any setting.

An ideal reactor should have a very small R/X ratio. However, there are obviously practical limits of R/X ratio below which a reactor tends to become unduly expensive and large. Thus the values of R/X given in table III of the circuit-unit reactors represent a compromise between reasonable cost and an acceptable R/X ratio.

In the design of the reactors, autotransformers, and mutual-reactance units, low losses and high permeability at the low flux densitites were desirable; consequently, nickel-iron-alloy magnetic cores were generally used.

The autotransformers are rated at 62.5 volts (125 per cent) and 250 milliamperes (500 per cent). The taps are accurate to plus or minus one per cent of the dial setting. The series reactance of these transformers is compensated with suitable series capacitors.

The mutual-transformer units are rated 62.5 volts (125 per cent) and 250 milliamperes (500 per cent). The two windings of this unit, a 1:1 ratio transformer, are wound together so that minimum leakage reactance is obtained. The relatively large capacity coupling resulting from the close spacing of the wires is compensated by means of a small reactor connected from one winding to the other.

The Motor-Generator Set

The motor-generator supplies three-phase, 480-cycle power at 440 volts through an autotransformer to the 12 analyzer generator units. Because of the low analyzer circuit voltage and currents used, the maximum 480-cycle input to the entire analyzer is less than 5 kva. The single-phase component is less than one kva.

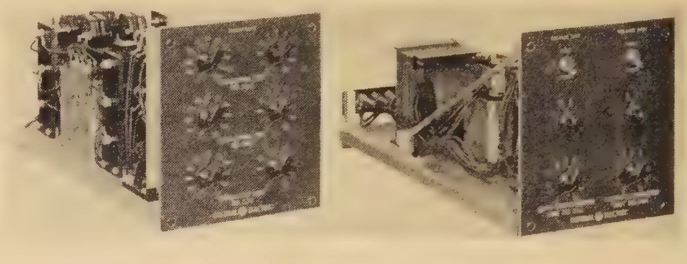

Figure 8. Capacitor and autotransformer units

In order to maintain substantially balanced voltages at the terminals of the three-phase generator with a single-phase load component, a phase balancer is connected in parallel with it. The phase balancer is directly coupled to the generator and rotates at synchronous speed. In addition to its voltage balancing action, the phase balancer absorbs a good deal of the small residual harmonic content of the voltage of the sine-wave generator. The phase balancer magnetizing current is compensated by means of suitable capacitors.

The complete motor-generator set assembly consists of

Table III. Typical R/X Ratios of Circuit-Unit Reactors

Circuit Unit	Reactance Setting (Per Cent)	R/X Ratio (Per Cent)
Line-impedance unit	0.2	8
	1.0	5.5
	10.0	3.5
	70.0	3.0
Load-impedance unit	5	5.0
	10	4.5
	100	3.5
	1,500	3.0

four machines, a 60-cycle driving motor, a 480-cycle alternator, a phase balancer, and an exciter, all directly coupled and mounted on a 20-inch-by-7-foot base.

In view of the small amount of 440-volt, 480-cycle power to be transmitted, the motor-generator set may readily be remotely installed from the analyzer. In the General Electric installation the distance is of the order of 200 feet and considerably larger distances are quite feasible.

Conclusions

The operation of the analyzer since it was completed has shown that the design has achieved the high degree of facility and speed of operation which was expected with a resultant saving roughly the equivalent of one operator. When the occasion arises the analyzer may be operated conveniently by a single operator. The over-all accuracy and accuracy of the component parts has been within the limits for which the equipment was designed.

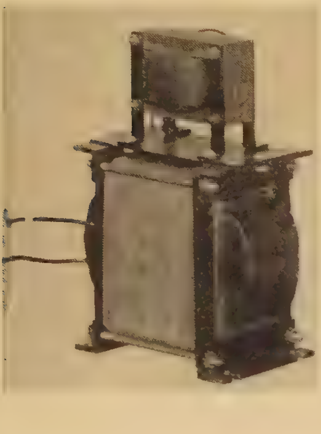

Figure 9. Mutual-reactance unit with compensating reactor

The following distinctive design features have contributed to the efficient analyzer performance:

1. The instruments and all selector-key switches are centrally arranged, so that the operator may take conveniently the desired readings of network quantities from one position in front of the instrument cabinet without assistance.

2. The concentration of the circuit unit connecting equipment in two cabinets facilitates the work of connecting the circuit units to form the network to be studied. In addition, the amount of transfer plugging, frequently a source of error, is materially reduced. With this arrangement the network busses may be formed on the plugging panels in the same relative positions which they have on the network diagram, affording easy checks of all connections.

3. The accurate light-beam-type instruments have a very short time of response and serve to measure voltage, current, watts, (vars) reactive voltamperes, and vector components of voltage and current with a minimum of eyestrain. In the measurement of these vector components and for reading phase angles an instrument Selsyn is used.

4. The instrument burdens have been reduced to very low values by the use of precision amplifiers of the stabilized type. Thus the introduction of the instruments in the network has a negligible effect on the existing distribution of voltage and current, resulting in a degree of accuracy of the measurements which precludes the need for correction of the measured results.

5. The close electrical tolerances to which all the component parts of the analyzer have been held, have resulted in the practical elimination of the use of correction tables for adjusting the network impedances to the values desired for the representation of the power network.

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The Properties of Three-Phase Systems Deduced With the Aid of Matrices

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ANY MATHEMATICAL process, even though fully developed in theoretical form, takes on more meaning, and thereby becomes more useful, if it is applied to familiar concepts. If in this application certain conclusions can be reached with ease which ordinarily are reached with difficulty, the utility of the mathematical process is still more conclusively demonstrated.

Three-phase circuits are very generally used. The simpler properties of such circuits have been considered, and have been taught in colleges for many years. There are, however, certain important properties of these systems, deduced in the following, which are not as widely known as they should be. The reason for this fact is simply that ordinarily the equations required to deduce these results get so cumbersome as the work progresses that the details hide the general properties of the system. Matrices are extremely effective in clearing away the complication of detail thus leaving the expressions for the general properties of the system more evident.

A further advantage of matrix nomenclature is that even to a beginner in the study of polyphase systems, after having mastered the matrix treatment of three-phase systems, the method of extending the details of the matrices to any other polyphase system will be evident.

The following treatment of three-phase systems shows the power of matrices, not only in simplifying the statement of the properties of circuits in general, but in determining the detailed properties of particular circuits. The method of manipulating matrices and of reaching certain conclusions from them is shown.

Preliminary

A nomenclature, convenient for all occasions when complex numbers, real numbers, vectors, and matrices are all used in the same discussion, is not easily established. The writer has found through his own investigations and through presenting the material to students that the following symbolism is simple and convenient: a matrix will be represented by the script symbols

$$\mathfrak{U}, \mathfrak{Y}, \mathfrak{Z}, \mathfrak{I}, \mathfrak{E}, \text{ etc.,}$$

a complex number or vector in the usual complex notation by

$$\boldsymbol{V}, \boldsymbol{I}, \boldsymbol{y}, \boldsymbol{z}, \text{ etc.,}$$

and a scalar or real number by the absolute value as

$$|V|, |I|, |y|, |z|, \text{ etc.}$$

This symbolism will be used in what follows.

The properties of matrices as given in the paper by Pipes[1] will be assumed, in as far as they are needed, in what follows. In addition, and in keeping with the nomenclature to be used in this discussion, the unit matrix will be designated as

$$\mathfrak{U}_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

Other unit matrices which will be used below, formed by shifting the last column successively to the first column position, are

$$\mathfrak{U}_2 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \text{ and } \mathfrak{U}_3 = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \qquad (2)$$

The following matrices will also be useful:

$$\mathfrak{U}_{12} = \mathfrak{U}_1 - \mathfrak{U}_2 \text{ and } \mathfrak{U}_{13} = \mathfrak{U}_1 - \mathfrak{U}_3 \qquad (3)$$

Note that the matrices given by equation 3 are singular.

Three-Phase Delta Connection

(*a*) *General:* In matrix notation the voltage equations in terms of the cyclic currents for figure 1—assuming no mutual inductance or capacitance—are

$$\mathfrak{E} = \mathfrak{Z}\,\mathfrak{I} \qquad (4)$$

where

$$\mathfrak{E} = (\boldsymbol{E}_{12}, \boldsymbol{E}_{23}, \boldsymbol{E}_{31}, 0) \qquad (5)$$

$$\mathfrak{I} = (\boldsymbol{I}_{12}, \boldsymbol{I}_{23}, \boldsymbol{I}_{31}, \boldsymbol{I}_4) \qquad (6)$$

and

$$\mathfrak{Z} = \begin{pmatrix} \boldsymbol{z}_{12}+\boldsymbol{z}_{2B}+\boldsymbol{z}_{BA}+\boldsymbol{z}_{A1} & -\boldsymbol{z}_{2B} & -\boldsymbol{z}_{A1} & -\boldsymbol{z}_{AB} \\ -\boldsymbol{z}_{2B} & \boldsymbol{z}_{23}+\boldsymbol{z}_{3C}+\boldsymbol{z}_{CB}+\boldsymbol{z}_{B2} & -\boldsymbol{z}_{3C} & -\boldsymbol{z}_{BC} \\ -\boldsymbol{z}_{A1} & -\boldsymbol{z}_{3C} & \boldsymbol{z}_{31}+\boldsymbol{z}_{1A}+\boldsymbol{z}_{AC}+\boldsymbol{z}_{3C} & -\boldsymbol{z}_{AC} \\ -\boldsymbol{z}_{AB} & -\boldsymbol{z}_{BC} & -\boldsymbol{z}_{AC} & \boldsymbol{z}_{AB}+\boldsymbol{z}_{BC}+\boldsymbol{z}_{CA} \end{pmatrix} \qquad (7)$$

The current and voltage matrices are to be considered as one columned, but are written as in equations 5 and 6 as a matter of convenience.

Further, since the impedance matrix is not singular,

$$\mathfrak{I} = \mathfrak{Y}\,\mathfrak{E}$$

where the admittance matrix is the inverse of the impedance matrix of 7.

The phase currents at the generator are

$$\mathfrak{I}_{pg} = (\boldsymbol{I}_{12}, \boldsymbol{I}_{23}, \boldsymbol{I}_{31}) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \mathfrak{I} = \mathfrak{T}_{pg}{}^{\Delta}\,\mathfrak{I} \qquad (8)$$

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1. For numbered reference, see end of paper.

and the phase currents at the load are

$$\mathfrak{I}_{pl} = (I_{BA}, I_{CB}, I_{AC}) = \begin{pmatrix}1&0&0&-1\\0&1&0&-1\\0&0&1&-1\end{pmatrix}\mathfrak{I} = \mathfrak{T}_{pl}{}^{\Delta}\,\mathfrak{I} \tag{9}$$

The line currents are

$$\mathfrak{I}_L = (I_{A1}, I_{B2}, I_{C3}) = \mathfrak{A}_{13}\mathfrak{I}_{pg} = \mathfrak{A}_{13}\mathfrak{I}_{pl} = \mathfrak{A}_{13}\mathfrak{T}_{pg}{}^{\Delta}\mathfrak{I} = \mathfrak{A}_{13}\mathfrak{T}_{pl}{}^{\Delta}\mathfrak{I} \tag{10}$$

Note, as is evident from figure 1 and equations 8 and 9, that $\mathfrak{I}_{pg} \neq \mathfrak{I}_{pl}$ even though equation 10 at first glance makes them appear so. The fact that the transformation matrix $\mathfrak{A}_{13}$ is singular makes this relation possible. Note further that $\mathfrak{I}_{pg}$ or $\mathfrak{I}_{pl}$ *cannot* be determined from $\mathfrak{I}_L$ since $\mathfrak{A}_{13}$ is singular, thus pointing out a fact which is not immediately evident from the equations themselves.

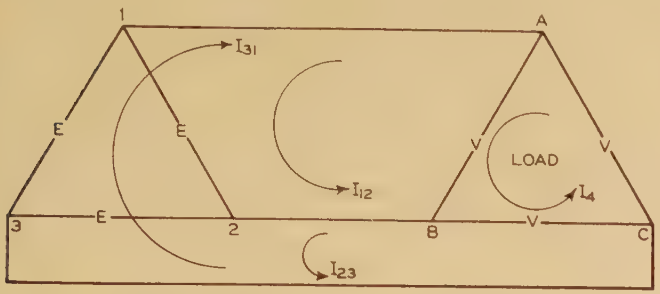

Figure 1. Three-phase delta connection

The line and phase voltages at the generator are

$$\mathfrak{E}_{Lg} = \mathfrak{E}_{pg} = \mathfrak{T}_{pg}{}^{\Delta}\,\mathfrak{E} = (E_{12}, E_{23}, E_{31}) \tag{11}$$

and the terminal voltages of the generator, in terms of the voltage drops of line and load, are

$$\mathfrak{V}_{pg} = \mathfrak{E}_{pg} - \mathfrak{V}_{ig} = \mathfrak{V}_{pl} + \mathfrak{A}_{12}\mathfrak{V}_L \tag{12}$$

where the load and line drops at the generator terminals are

$$\mathfrak{V}_{pg} = (V_{21}, V_{32}, V_{13}) \tag{13}$$

the internal generator drops are

$$\mathfrak{V}_{ig} = \begin{pmatrix}z_{12}&0&0\\0&z_{23}&0\\0&0&z_{31}\end{pmatrix}\mathfrak{I}_{pg} = \mathfrak{Z}_g\,\mathfrak{I}_{pg} \tag{14}$$

the line drops are

$$\mathfrak{V}_L = \begin{pmatrix}z_{A1}&0&0\\0&z_{B2}&0\\0&0&z_{C3}\end{pmatrix}\mathfrak{I}_L = \mathfrak{Z}_L\,\mathfrak{I}_L \tag{15}$$

and the phase drops at the load are

$$\mathfrak{V}_{pl} = \begin{pmatrix}z_{AB}&0&0\\0&z_{BC}&0\\0&0&z_{CA}\end{pmatrix}\mathfrak{I}_{pl} = \mathfrak{Z}_l\mathfrak{I}_{pl} \tag{16}$$

Other relations may be readily set up to handle any particular problem. Some special cases of interest are given in the following.

(*b*) *Balanced Voltages and Unbalanced Load Impedances.* In order to simplify the expressions and still retain enough of the circuit for present purposes, assume that all impedances of figure 1 are zero except the three load impedances. Then since the voltages are assumed as balanced—*acb* phase sequence—

$$\mathfrak{V}_{pl} = V_{BA}\,(1, a, a^2) \tag{17}$$

where

$$a = \epsilon^{j\frac{2\pi}{n}} = \epsilon^{j\frac{2\pi}{3}} = \epsilon^{j120}$$

Also from equations 10 and 16

$$\mathfrak{I}_L = \mathfrak{A}_{13}\mathfrak{I}_{pl} = \mathfrak{A}_{13}\mathfrak{Y}_l\mathfrak{V}_{pl} \tag{18}$$

But since

$$\mathfrak{Y}_l = \begin{pmatrix}\frac{1}{z_{AB}}&0&0\\0&\frac{1}{z_{BC}}&0\\0&0&\frac{1}{z_{CA}}\end{pmatrix} = \begin{pmatrix}y_{AB}&0&0\\0&y_{BC}&0\\0&0&y_{CA}\end{pmatrix}$$

equations 17 and 18 give

$$\mathfrak{I}_L = \begin{pmatrix}y_{AB}&0&-y_{CA}\\-y_{AB}&y_{BC}&0\\0&-y_{BC}&y_{CA}\end{pmatrix} V_{BA}\,(1, a, a^2)$$

which multiplied out gives

$$\mathfrak{I}_L = V_{BA}\,(y_{AB}-a^2y_{CA},\ -y_{AB}+ay_{BC},\ -ay_{BC}+a^2y_{CA}) \tag{19}$$

But if the balanced voltage phase-sequence is changed to the *abc* sequence

$$\mathfrak{V}_{pl} = V_{BA}\,(1, a^2, a),$$

and

$$\mathfrak{I}_L = V_{BA}\,(y_{AB} - ay_{CA},\ -y_{AB} + a^2y_{BC},\ - a^2y_{BC} + ay_{CA}) \tag{20}$$

Examining these two relations—19 and 20—makes it evident that, for any set of load impedances such that their phase angles, or the ratio x/r, is the same for all three impedances, the *magnitude of the line currents will not change* under a change in phase sequence of voltage; and that for any other impedance relation the line currents will change in magnitude with a change in the phase sequence of the voltages.

(*c*) *Unbalanced Voltages and Balanced Impedances.* Considering load impedances only, evidently

$$\mathfrak{Y}_l = y\mathfrak{A}_1 \tag{21}$$

Further, if n' is located at the center of gravity of the load voltage triangle, and if

$$\mathfrak{V}_{N'} = (V_{N'A}, V_{N'B}, V_{N'C}) \tag{22}$$

then

$$\mathfrak{V}_{pl} = (V_{BA}, V_{CB}, V_{AC}) = \mathfrak{A}_{12}\,\mathfrak{V}_{N'} \tag{23}$$

But from 18, 21, and 23

$$\mathfrak{I}_L = \mathfrak{A}_{13}\,y\,\mathfrak{A}_1\,\mathfrak{A}_{12}\,\mathfrak{V}_{N'} = y\mathfrak{A}_{13}\,\mathfrak{A}_{12}\,\mathfrak{V}_{N'} \tag{24}$$

which gives

$$\mathfrak{I}_L = y\begin{pmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{pmatrix}\mathfrak{V}_{N'} = 3y\,\mathfrak{V}_{N'} \tag{25}$$

This relation shows immediately that the line currents are associated with the voltages to the center of gravity of the

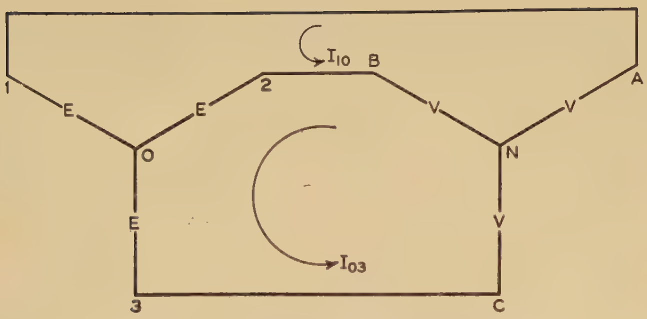

Figure 2. Three-phase wye connection

voltage triangle by the phase angle of the load impedances. Also note that the voltages to the center of gravity may be determined from

$$\mathfrak{V}_{N'} = \frac{1}{3y}\mathfrak{I}_L \tag{26}$$

(*d*) *Balanced Voltages and Balanced Impedances.* Once more considering the load only—*acb* phase sequence—

$$\mathfrak{I}_{pl} = I_{BA}\,(1, a, a^2)$$

$$\mathfrak{I}_L = \mathfrak{U}_{13}\,\mathfrak{I}_{pl} = I_{BA}\mathfrak{U}_{13}\,(1, a, a^2)$$

$$\mathfrak{I}_L = \sqrt{3}\,\epsilon^{j30}\,\mathfrak{I}_{pl} \tag{27}$$

Also since the relation between line and phase currents is now simply a complex number rather than a singular matrix

$$\mathfrak{I}_{pl} = \frac{\epsilon^{-j30}}{\sqrt{3}}\mathfrak{I}_L \tag{28}$$

Three-Phase Wye Connection

(*a*) *General.* The voltage equations in terms of cyclic currents for figure 2—assuming no mutual inductance or capacitance—are, in matrix form,

$$\mathfrak{E} = \mathfrak{Z}\,\mathfrak{I} \tag{29}$$

where

$$\mathfrak{E} = (E_{12}, E_{23}) \tag{30}$$

$$\mathfrak{I} = (I_{10}, I_{03}) \tag{31}$$

and

$$\mathfrak{Z} = \begin{pmatrix} z_{10}+z_{20}+z_{2B}+z_{BN}+z_{NA}+z_{A1} & -z_{02}-z_{2B}-z_{BN} \\ -z_{02}-z_{2B}-z_{BN} & z_{03}+z_{02}+z_{3C}+z_{CN}+z_{NB}+z_{2B} \end{pmatrix} \tag{32}$$

Of course, since $\mathfrak{Z}$ is nonsingular

$$\mathfrak{I} = \mathfrak{Y}\,\mathfrak{E}$$

The line currents of the wye system are

$$\mathfrak{I}_L = (I_{A1}, I_{B2}, I_{C3}) = \mathfrak{I}_{pg} = \mathfrak{I}_{pl} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix}\mathfrak{I} = \mathfrak{T}_y\,\mathfrak{I} \tag{33}$$

The voltages are

$$\mathfrak{E}_{Lg} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ -1 & -1 \end{pmatrix}\mathfrak{E} \text{ and } \mathfrak{E} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}\mathfrak{E}_{Lg} \tag{34}$$

and in terms of phase voltages

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}\mathfrak{E}_{pg}$$

Also

$$\mathfrak{E} = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{pmatrix}\mathfrak{E}_{pg} = \mathfrak{T}_{yt}\,\mathfrak{E}_{pg} \tag{35}$$

The subscript t will be used to denote the transpose of a matrix. The singular transformation matrices indicate that the generator phase voltages cannot be determined from $\mathfrak{E}$ or from the generator line voltages.

If the impedances of the system are written as diagonal matrices

$$\mathfrak{Z}_l = \begin{pmatrix} z_{AN} & 0 & 0 \\ 0 & z_{BN} & 0 \\ 0 & 0 & z_{CN} \end{pmatrix} \quad \mathfrak{Z}_L = \begin{pmatrix} z_{A1} & 0 & 0 \\ 0 & z_{B2} & 0 \\ 0 & 0 & z_{C3} \end{pmatrix} \quad \mathfrak{Z}_g = \begin{pmatrix} z_{01} & 0 & 0 \\ 0 & z_{02} & 0 \\ 0 & 0 & z_{03} \end{pmatrix} \tag{36}$$

the generator voltages in terms of the currents are

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}\,(\mathfrak{Z}_l + \mathfrak{Z}_L + \mathfrak{Z}_g)\,\mathfrak{I}_{pg} \tag{37}$$

Since $\mathfrak{U}_{12}$ is singular this transformation is singular, and, therefore, not reversible. However, the phase currents at the generator may be determined from equation 33 as

$$\mathfrak{I}_{pg} = \mathfrak{T}_y\,\mathfrak{Y}\mathfrak{E} \tag{38}$$

which gives from 34

$$\mathfrak{I}_{pg} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix}\mathfrak{Y}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}\mathfrak{E}_{Lg}$$

Also from 38 and 35

$$\mathfrak{I}_{pg} = \mathfrak{T}_y\,\mathfrak{Y}\,\mathfrak{T}_{yt}\,\mathfrak{E}_{pg} \tag{39}$$

This equation cannot be used to determine $\mathfrak{E}_{pg}$ in terms of $\mathfrak{I}_{pg}$ because of the singularity of the transformation. Further investigation will show that no relation can be found for $\mathfrak{E}_{pg}$ in terms of $\mathfrak{I}_{pg}$ and the circuit impedances or admittances; i. e., given a set of wye-connected impedances and the line currents, the phase generator voltages of the source cannot be computed. There is an infinite set of these phase voltages which will satisfy the system.

(*b*) *Balanced Voltages and Unbalanced Load Impedances.* Using 39 and the fact that

$$\mathfrak{E}_{pg} = E_{10}\,(1, a, a^2)$$

for the 132 sequence, a relation corresponding to the delta circuit relation may be deduced; namely, that if the three-phase impedances have the same ratio x/r, a change of phase sequence will not affect the current magnitudes.

(*c*) *Unbalanced Voltages and Balanced Load Impedances.* Assuming all but load impedances as negligible, equation 32 reduces to

$$\mathfrak{Z} = \begin{pmatrix} 2z & -z \\ -z & 2z \end{pmatrix} = z\begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix} \text{ and}$$

$$\mathfrak{Y} = \frac{1}{3}\begin{pmatrix} 2y & y \\ y & 2y \end{pmatrix} = \frac{y}{3}\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$$

Then from 39

$$\mathfrak{I}_L = \mathfrak{I}_{pg} = \frac{y}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\mathfrak{E}_{pg} \tag{40}$$

If $E_{10} + E_{20} + E_{30} = 0$ this relation becomes

$$\mathfrak{I}_L = \mathfrak{I}_{pg} = y\,\mathfrak{E}_{pg}$$

A further property of this system may be deduced as follows: the phase drops at the load are

$$\mathfrak{V}_{pl} = \mathfrak{Z}_l \mathfrak{I}_{pg} = z\,\mathfrak{U}\;\mathfrak{I}_{pg} = z\,\mathfrak{I}_{pg} \tag{41}$$

Further, in terms of the voltages to the center of gravity of the generator voltage triangle,

$$\mathfrak{E} = \mathfrak{T}_{yt}\,\mathfrak{E}_{pg}' = \mathfrak{T}_{yt}\,(E_{10}', E_{20}', E_{30}') \tag{42}$$

and from 38 and 42

$$\mathfrak{I}_{pg} = \mathfrak{T}_y \mathfrak{Y} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' = \frac{1}{3}\,y\,\mathfrak{T}_y \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' \tag{43}$$

Hence from 41 and 43

$$\mathfrak{V}_{pl} = \frac{1}{3}\,\mathfrak{T}_y \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \mathfrak{E}_{pg}' \tag{44}$$

But since $E_{10}' + E_{20}' + E_{30}' = 0$

$$\mathfrak{V}_{pl} = \mathfrak{E}_{pg}' \tag{45}$$

which shows that the neutral or common point of the load voltages is at the center of gravity of the line voltage triangle.

(*d*) *Balanced Voltages and Impedances.* The voltages are—sequence *acb*—

$$\mathfrak{V}_L = \mathfrak{U}_{12} \mathfrak{V}_{pl} = \mathfrak{U}_{12} V_{NA}\,(1, a, a^2)$$
$$\mathfrak{V}_L = \sqrt{3}\,\epsilon^{-j30}\,\mathfrak{V}_{pl} \tag{46}$$

Also the phase voltages may for this special case be determined from the line voltages as

$$\mathfrak{V}_{pl} = \frac{\epsilon^{j30}}{\sqrt{3}}\,\mathfrak{V}_L \tag{47}$$

Further from 39 and the conditions here being considered

$$\mathfrak{I}_{pg} = y\mathfrak{E}_{pg} = y\mathfrak{V}_{pl} \tag{48}$$

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A System of Electric Remote-Control Accounting

By L. F. WOODRUFF
MEMBER AIEE

THE ACCOUNTING system which will be outlined in this paper will be discussed mainly in its application to a department store. However, it will not require any great stretch of the imagination to visualize the application of the same system and devices to other fields, including factory production control and pay rolls, public-utility accounts receivable, and others.

The Punched-Card Method

The punched-card method of accounting by automatic machinery has had a steady growth since its use in the United States census tabulation of 1890. At the present time the method is used in the great majority of large corporations, and literally *billions* of cards are used every year in this country alone.

In its simplest elements, the method involves the preparation of cards through which are punched holes in certain coded positions to represent numbers, or, more rarely, letters of the alphabet. The cards after preparation are stacked in hoppers of automatic machines, through which they are fed one by one, and the coded numbers picked up by electrical or mechanical sensing devices. These sensing devices in turn control adding units or other devices which do the actual accounting. There are machines for sorting, adding, subtracting, and multiplying, and these have many kinds of automatic controls which it would be out of place to describe in detail here.

The system of remote-control accounting which it is proposed to describe is not a complete system in itself, but has been designed as an aid and adjunct to extend the field of economical application of the punched-card method.

The Economical Application of the Punched-Card Method

The punched-card method is usually found to be economical of application where large masses of numerical data must be handled accurately and totaled in numerous groupings. Small quantities of data may be handled well on the machines, but the costs of handling on punched cards are much more favorable if there is enough work to keep at least a full set of machines busy continuously. The speeds and capacities of the machines are so great (400 cards per minute for the sorters, 150 per minute for the tabulators) that large masses of data are required to keep the machines usefully employed.

It should be clear also that when the cards have once been prepared (i.e., punched and checked) it is a relatively easy matter to run off a new set of statistics from them by sorting them automatically into new groupings, and tabulating them in these groupings. The more groupings into which it is desired to tabulate and totalize the information, the smaller the fraction of the card cost and punching cost which should properly be allocated against each tabulation, and therefore the method shows up most favorably when there are numerous groupings to be handled.

The census, which was the first application of the punched-card method, still stands out as the ideal type of job in its great mass of data and numerous segregations desired.

It should not be inferred that where the number of segregations is small, the punched-card method is undesirable, because other factors than direct cost, such as speed and precision, may be controlling factors. Other things being equal, however, it is unquestionably true that the most favorable applications are as has been stated. By way of illustration we may note that some of the most successful, widely adopted, and long continued applications have been in the fields of insurance, chain groceries, factory production control, and payroll. In insurance, the cards are used for many forms of actuarial analysis as well as for handling the specific dollar accounting of the policy holders individually. In chain grocery warehousing, a single card can be used in turn as an on-order record, for making a tally list for checking merchandise received, as a record in a perpetual inventory, as an order to ship to an individual retail store, and as a billing medium to that store. Thereafter, with additional data of store identification and date of shipment punched in, it is available with other cards to furnish various analyses of store performance, turnover of merchandise, profit by manufacturer, etc., etc. It would perhaps become tedious to describe in a similar vein the various uses to which a punched card is put in the other applications which have been mentioned.

There are of course accounting problems which involve so few segregations of data that they are not suitable for solution by the punched-card method, and there are others in which the advantages and disadvantages neutralize; and this in spite of a large volume of data.

In one or the other of these last two classifications lie most of the phases of accounting and control in large department stores. There have been dozens of punched-card installations in department stores, but many of these after thorough trial have been discontinued. It is apparent then that the executives in this large field are receptive to the idea, and that there are many advantages in its appli-

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1. For all numbered references, see list at end of paper.

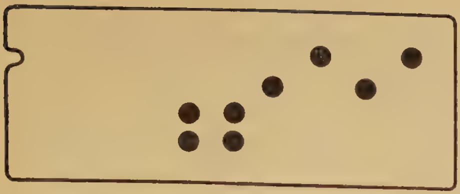


Figure 1. Punched token

cation, but these are just about offset by the disadvantages, which include the costs. Since this situation seemed favorable to the application of an auxiliary development, and further since the accounting problems of department stores are more standardized than, say, those of manufacturing plants, while yet offering comparable volume, the department store was selected as the field of the first experimental installation of remote-control accounting.

The magnitude of the department store accounting problem can be appreciated from a few statistics. There are approximately 300 department stores and departmentized specialty stores in the United States which do an annual business of over one million dollars per year, and the aggregate net sales of this group is about 4 billion dollars per year. An average store in this group would do about 13 million dollars of business per year. Using the percentage expense figures given in the Harvard Business School reports,[1] the payroll expense alone for accounts receivable, accounting office and credit, and marking, is in excess of two per cent of sales or $260,000 per year for

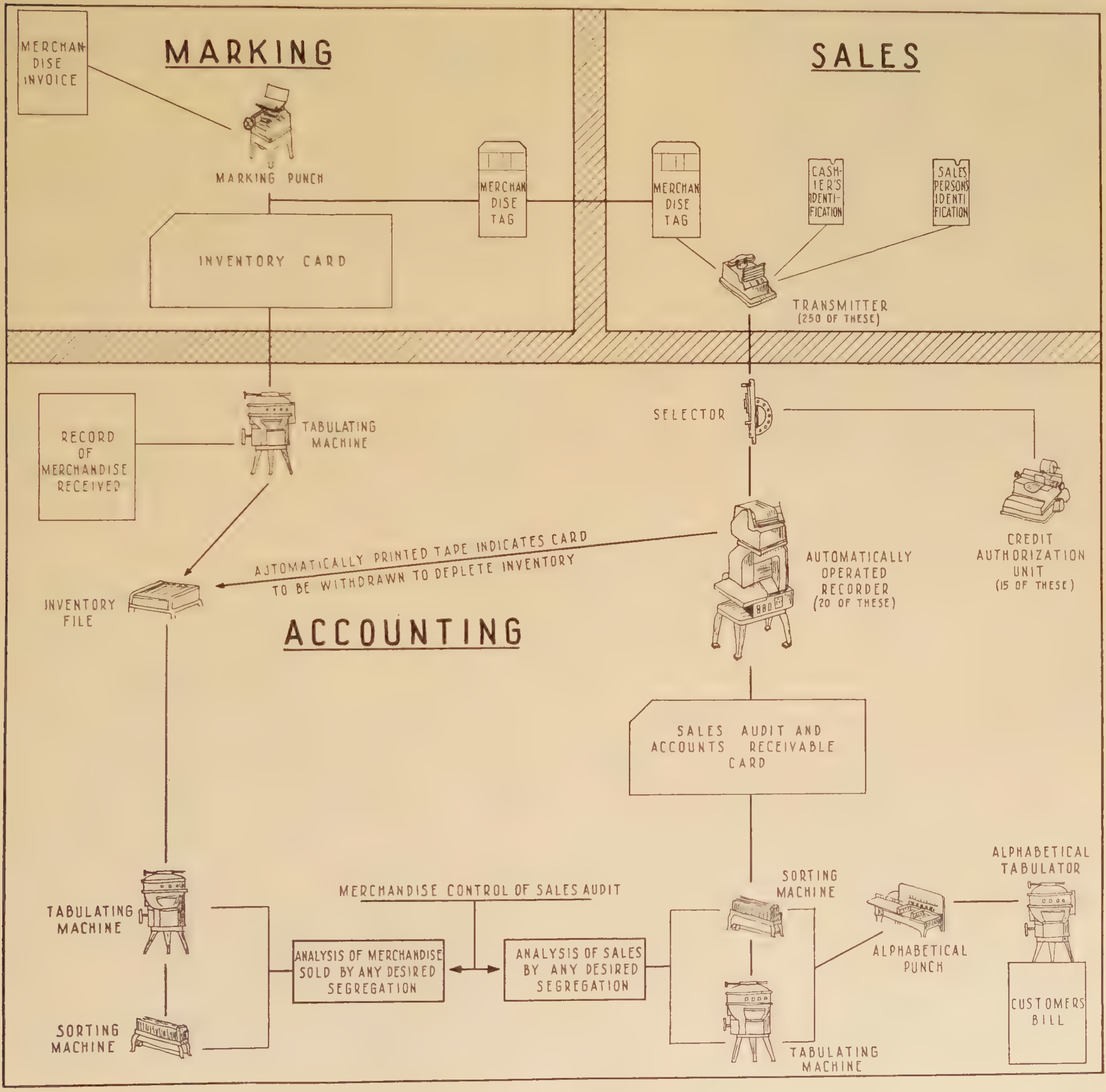

MARKING
MERCHANDISE INVOICE
MARKING PUNCH
MERCHANDISE TAG
INVENTORY CARD
SALES
MERCHANDISE TAG
CASHIER'S IDENTIFICATION
SALES PERSONS IDENTIFICATION
TRANSMITTER (250 OF THESE)
RECORD OF MERCHANDISE RECEIVED
TABULATING MACHINE
SELECTOR
CREDIT AUTHORIZATION UNIT (15 OF THESE)
AUTOMATICALLY PRINTED TAPE INDICATES CARD TO BE WITHDRAWN TO DEPLETE INVENTORY
INVENTORY FILE
AUTOMATICALLY OPERATED RECORDER (20 OF THESE)
ACCOUNTING
SALES AUDIT AND ACCOUNTS RECEIVABLE CARD
ALPHABETICAL TABULATOR
MERCHANDISE CONTROL OF SALES AUDIT
SORTING MACHINE
TABULATING MACHINE
ANALYSIS OF MERCHANDISE SOLD BY ANY DESIRED SEGREGATION
ANALYSIS OF SALES BY ANY DESIRED SEGREGATION
ALPHABETICAL PUNCH
CUSTOMERS BILL
SORTING MACHINE
TABULATING MACHINE

Figure 2. Chart of operating procedure

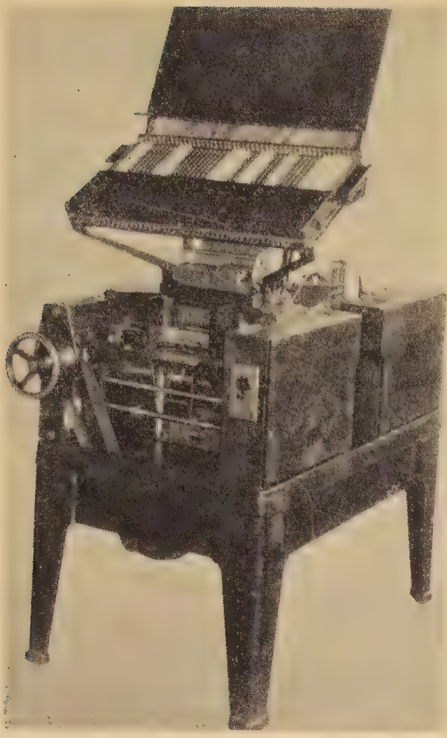


Figure 3. Duplex marking punch

the average store of the group. Such a typical store maintains well over $100,000 worth of accounting machines of various kinds to expedite its operations. An automatic or semiautomatic accounting system thus is seen to have considerable possibility of effecting actual savings in out-of-pocket expense, entirely aside from benefits which may be derived from better and more complete analysis, including speedier and more precise results.

The principal subdivisions of the detail mass accounting and related activities in department stores are inventory control, buying, marking, recording of sales, charge authorization, sales audit, accounts receivable, and accounts payable. In the usual present method, sales are recorded on sales slips except in a few small-goods departments where cash registers only are used. The sales audit is accomplished by sorting the sales checks manually into different groupings for different analyses and totalizing under each grouping. Lost checks are a continual source of worry. Poor handwriting and errors of recording by low-wage employees are handicaps. For each analysis there must be a separate sort, making the manual method slow and costly; and because of this a comprehensive analysis of sales is not economically feasible. A number of stores have already used punched-card machines in the sales audit, but approximately half of these stores have discontinued the punched-card method and gone back to their old plan. A considerable number of stores still continue to use punched cards in sales audit, but it is apparent from the history of the whole group that the benefits are not conclusive evidence of the superiority of that method. The obstacles to the use of punched cards in this work are that the average unit sale is small (about two dollars),[1] the number of groupings required for analysis is not large, and the expense of punching and checking each card from the sales check is too great to permit of any great saving being made by the use of the machines.

Inventory Control

In inventory control, there are two general methods in use at the present time. One method is the so-called *dollar control*, and the other the *unit control*.

Under the dollar method of inventory control, there is allotted to each department a certain sum of money with which to do business. With the amount so allotted, the buyer in charge of the department buys merchandise and conducts business much as though he were an independent merchant. Other than a knowledge of whether or not he is giving to the store a fair return upon the money invested in the department, and a periodical physical inventory taken to see that the dollar value of merchandise on hand is not excessive, the store executives have very little check upon the buyer. It may well be that the buyer is earning a fair return upon the capital invested in his department by "turning over" a small part of his stock a relatively great number of times per year, while the remainder is turned over but once or twice. Even the buyer himself has not at his disposal proper facilities for giving him de-

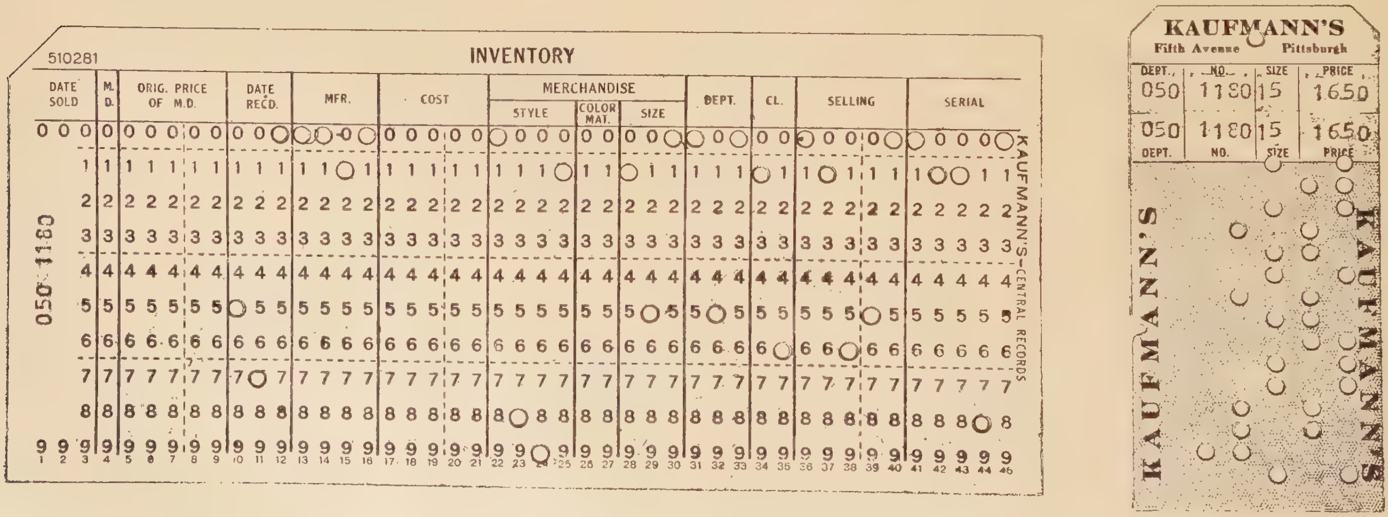


Figure 4. Unit inventory card and corresponding price tag

tailed knowledge of the merchandise in his department, and its turn-over.

Under the unit method of inventory control, a record is kept of each individual article of merchandise as it comes into the store. When each article of merchandise is sold, immediate note of the sale is made on the inventory records so that there is kept a running up-to-date record of the inventory on hand. Under this method, the executives and department heads may know at all times not only the dollar value of merchandise on hand but also just what the description is of this merchandise. They are able to determine what merchandise is moving and what is not, also what merchandise is being handled at a profit and what is not. Under this method, it is possible to keep the inventory at the lowest point consistent with having a sufficient amount and variety of merchandise on hand to meet the requirements of customers. This is the ideal method of inventory control, but because of the cost and the difficulty involved in the keeping of the necessary records, its use in department stores has necessarily been limited.

There are advantages and disadvantages in the recording of sales by cash register only as against the use of the sales book. Using the register, there is more opportunity for theft, and in the aggregate this is known to be very appreciable. Cash-register receipts for various amounts are soon scattered all over the floor in many sales areas. They offer no means of identifying the particular merchandise sold. On the other hand, cash registers are quick and do not waste time of either customer or sales person. Sales slips are more widely used in department stores. If they are used in connection with carrier systems, usually tubes, there is a time-consuming wait for change and receipt, aggravating to the customer. During busy seasons some departments are temporarily changed over from sales-slip to cash-register recording so as to increase the speed of handling transactions.

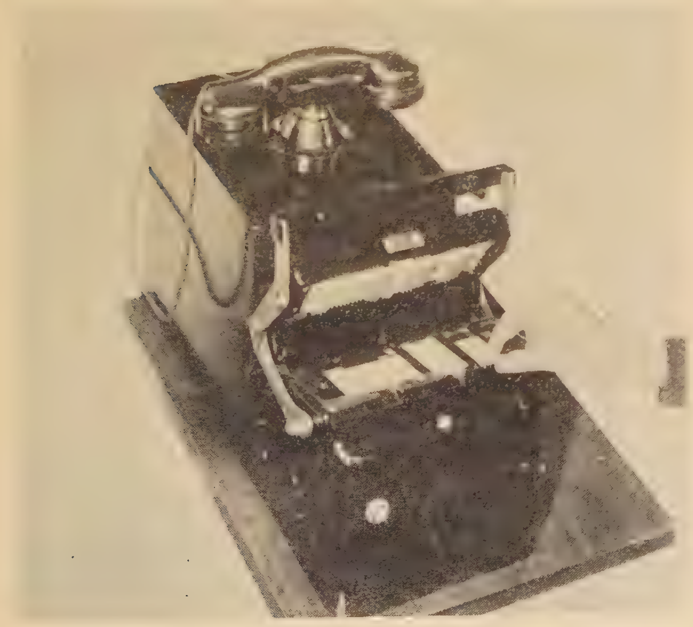
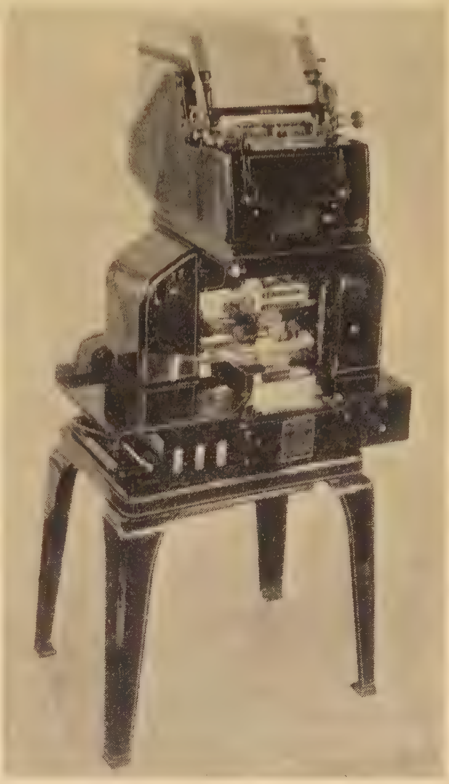


Figure 5. Central records transmitter

Outline of Operations of Remote-Control Accounting System

The factors involved in a sale are: (1) the customer, (2) the merchandise and its selling price, (3) the sales person, and (4) the cashier. In the system to be described, each of these factors is identified by a small punched tag, illustrated in figure 1. In a charge transaction, identification of the cashier is unnecessary. In a cash transaction, identification of the customer is unnecessary. In any one sale therefore it is necessary to identify only three of the four factors. These punched tags are used to control the reproduction, by mechanical and electrical means, of the information contained thereon, on a standard punched card. Then by usual methods of handling, the reproduced cards may be sorted and tabulated automatically to perform the major accounting operations.

Figure 6. Central records recorder



The detailed operation of the system may be understood best by following the chart of operating procedure, figure 2, in connection with the description.

In the marking room, a specially-developed machine (figure 3) simultaneously prints and punches standard tabulating cards for inventory record, and price tags for display and mechanical reproduction at the time of sale. For goods whose value and character warrant the expense of unit control, an individual card and tag are prepared for each piece. For other types of merchandise there are variations in the system, which will not be described in detail. A typical unit inventory card and the corresponding price tag are shown in figure 4. The inventory cards are tabulated and listed, and totals checked against

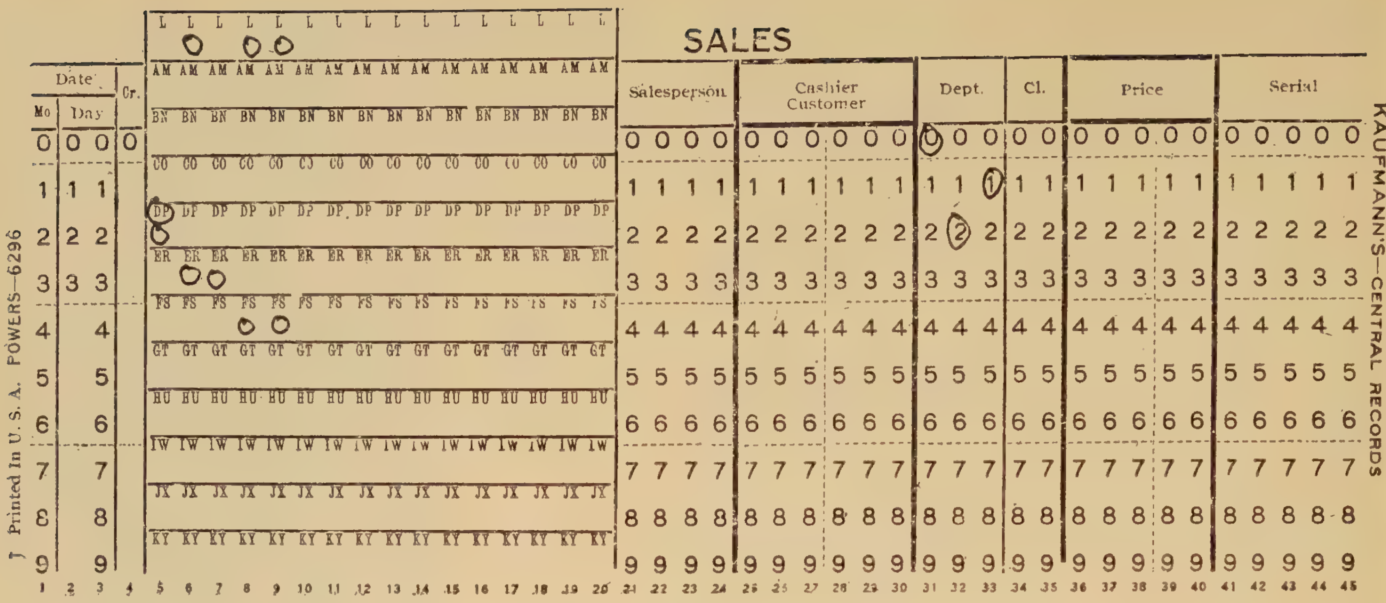


Figure 7. Sales record card

the invoices. It is to be noted that these cards and the price tags are both prepared by a single keyboard setup on the duplex punch illustrated in figure 3, and that a check of the inventory cards is also a check of the price tags. After checking, the inventory cards go to the stock file, and the price tags are attached to the merchandise and go with it to the sales area. An important point in the marking procedure is that the punching is done on a quantity basis, and not item by item. A shipment of merchandise may contain 500 items, and if 500 unit inventory cards are to be prepared, most of the information will be common to all, and but a single keyboard setup will be required for this common information. If this information is checked for one card, it is checked for all. There will be of course some information which is not common to all, but the keyboard changes made in one field of the card do not disturb those in other fields. When producing duplicate cards and tags, the marking punch shown in figure 3 has an output of 100 per minute.

Let us follow the tagged merchandise to the sales area. When a piece of merchandise is sold for cash, the merchandise tag is torn from its stub, which contains duplicate printing of the merchandise identification for use in case the merchandise is returned for credit later by the customer. The detached portion of the tag, along with a punched celluloid token bearing in code the identificaton number of the sales person, and a similar token for the cashier, are placed in a *transmitter*, illustrated in figure 5. When the top of the transmitter is closed (provided it contains all three of the tokens), through appropriate wiring and automatic selector switches it is immediately connected to an idle *recorder* (figure 6) in a central accounting office. All the information needed for a complete record of the sale is automatically transmitted from the punched tokens and reproduced on a standard punched card, and is also printed and totaled on the recording machine.

Transmitting the record of the sale takes five seconds, and at its completion the merchandise tag is automatically stamped with the date of sale, and the top of the transmitter opens. The stamped tag is given to the customer as a receipt, and it identifies the exact merchandise and the price at which it has been sold.

The sales record card produced at the central office is reproduced in figure 7. All the information punched on the right-hand half of the card is obtained from the transmitter. The date only, which occupies the extreme left-hand field on the card, is set up each morning on the recorder punches, and reproduces on all cards punched that day. The large alphabetical field in the left central part of the card is not used on cards which record cash transactions.

The sales audit is obtained from the sales cards by sort-

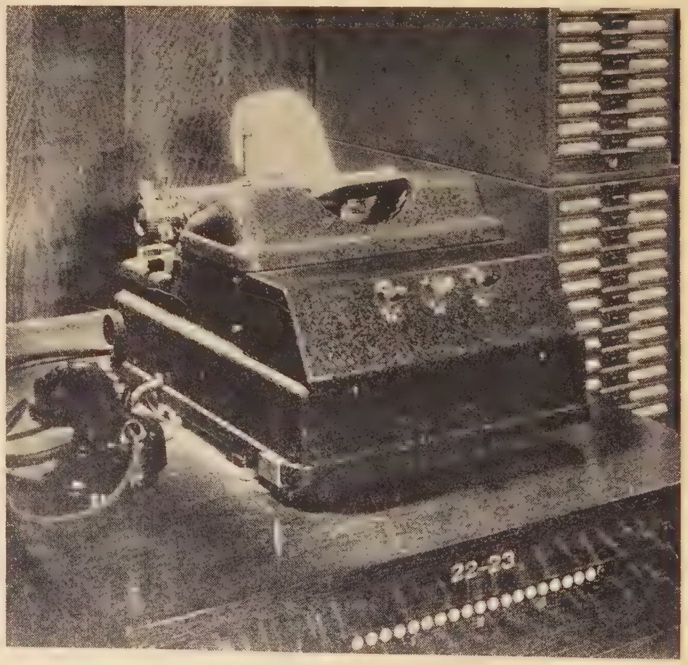


Figure 8. Charge authorizing unit

ing and tabulating them by machine in the usual way. This part of the work includes reports of cash by cashier, sales by sales person, sales by department, and for the entire store.

The merchandise piece number or serial number on the sales record card serves as a means of identifying, in the inventory file, the inventory card corresponding to the item sold. This card is withdrawn, and with similar cards serves as a basis for the analysis of merchandise sold by any desired segregation. The cards are "gang punched" with the date of sale. Among the reports which have been found most useful from these cards are analyses of fastest selling items and styles, turnover by manufacturer, turnover by department, number of items by size, gross profit by manufacturer and by department, and sales by price lines. All these analyses and many more are obtained without any further detail work, but merely by the operation of sorters and tabulators whose speeds are respectively 400 cards per minute and 150 cards per minute. There is a possibility of human error coming in during the operation of withdrawing the inventory cards from the file, but this has been practically eliminated by *totaling the serial numbers* of the sales record cards, which is done automatically, and if the totals check the probability of error is very small indeed.

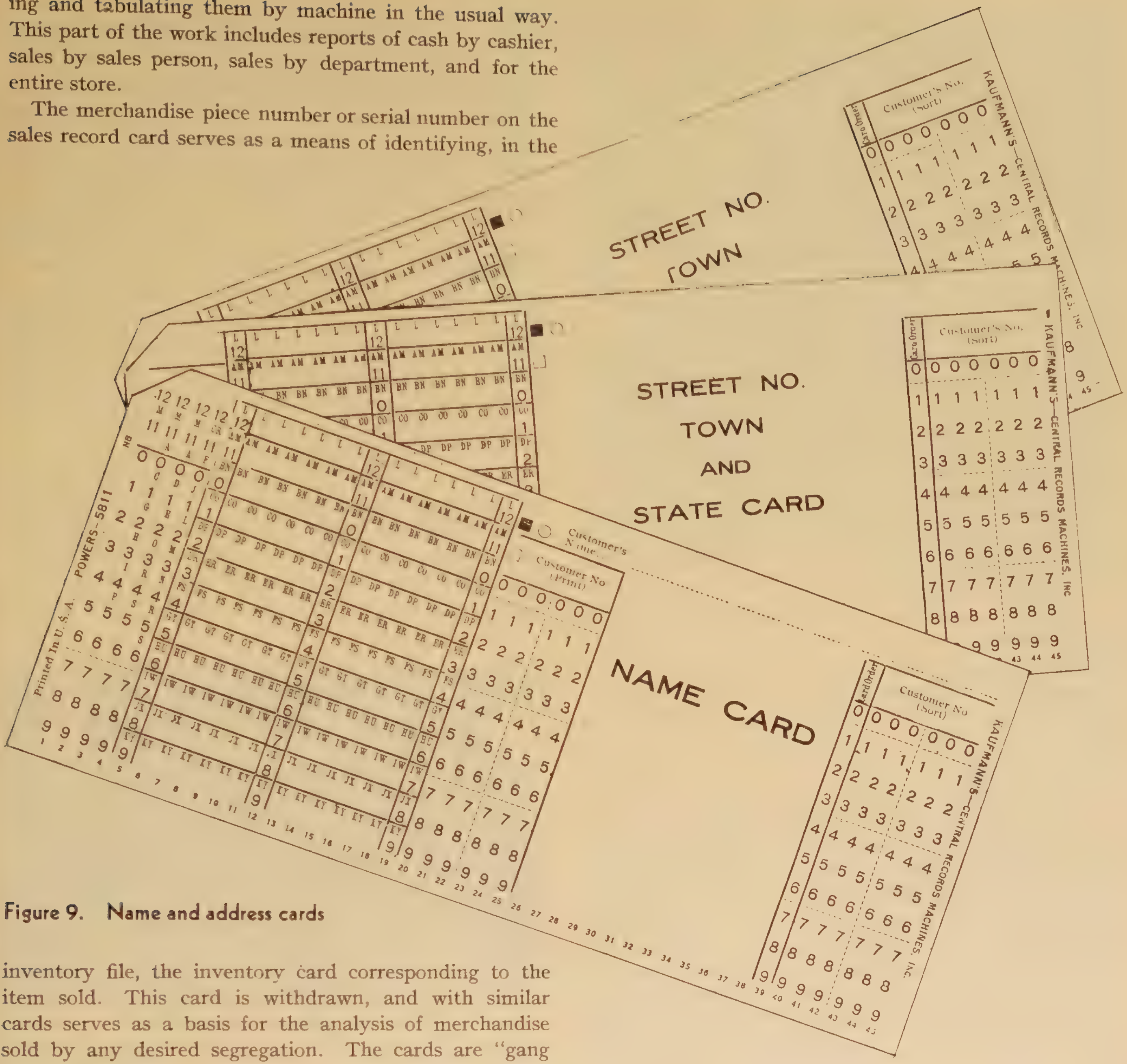


Figure 9. Name and address cards

The cards remaining in the file represent merchandise on hand, and highly useful and valuable information can be drawn from them. Reports which were regularly prepared from this file in a large experimental installation included a weekly summary of merchandise on hand; a monthly analysis by department of the age of merchandise on hand in dollar value and in pieces; an analysis of markdowns for the month by manufacturer, by price line and by reason; a monthly analysis of returns to manufacturer; a quarterly analysis of merchandise in each department classified by size, and size distribution for sales and inventory compared and brought into proper balance.

A file of "on order" cards is also maintained, and used as a basis for analysis of merchandise on order.

Charge Sale

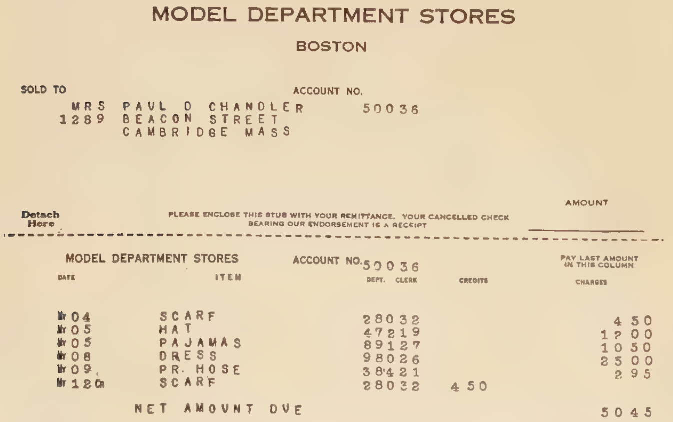
When a sale is made to a customer who has a charge account, there is a somewhat different procedure. All charge customers are supplied with punched celluloid identification tokens, similar to the usual charge tokens except that the account number is punched in code. In the recording of a charge sale, the customer's charge token is placed in the transmitter in the position used for the cashier's token in a cash sale. One additional step not necessary in the cash sale is necessary for the charge sale. This is the *charge authorization.* The circuits of the transmitter distinguish between the charge tokens and the cashiers' tokens by the range of numbers assigned to each, and if the number lies in the charge account range, the automatic switching equipment does not immediately establish a connection between transmitter and idle recorder, but first connects the transmitter to a *charge authorizing unit,* illustrated in figure 8. This machine receives from the transmitter and prints on a tape the customer's charge account number and the amount of the sale. The charge authorizing clerk refers to a visible-index quick-reference file, part of which is shown in the illustration, to see if the condition of the account warrants the approval of the credit. If so, she operates the button marked OK, and this results in the establishing of connection between the transmitter and an idle recorder, and the transmitting of the record of the sale. The credit authorizing machine makes notation on the tape that the credit has been approved.

It may be noted that cash sales records and charge sales records are routed indiscriminately to any recorder which happens to be idle, and the sales record cards representing the two types of sale are sorted later on to separate the two types.

Customer Billing

After the charge sales record cards have been used in the preparation of the sales audit, along with the cards representing the cash sales, they are used in the performance of the accounts receivable billing. The charge cards are sorted by department and then by merchandise classification within the department. They are then "gang punched" in the alphabetical field with *name* of the item or classification, after which they are sorted again by account number. The cards are now filed in the accounts receivable file, which is arranged by account number. During this work a dollar total by ledger groups is used as a control check.

The accounts receivable file for each account contains a series of name-and-address cards, illustrated in figure 9. These serve as index cards in the file, and also act to head up the bill when the cards are fed through an alphabetical tabulator. At the beginning of each month a new card is inserted for each active account, showing the balance of the account at the end of the preceding month. As transactions occur, other cards are inserted into the account file for sales, cash payments, merchandise returns for credit, etc. At the end of the fiscal month all the cards in the file, including the name-and-address cards, are run through a printing tabulator. The customers' bills are produced automatically, together with the total amount due, as illustrated in figure 10. The tabulating machine also carries along a total for all the bills in each ledger group for control and checking purposes.



MODEL DEPARTMENT STORES

BOSTON

SOLD TO
ACCOUNT NO.
MRS PAUL D CHANDLER 50036
1289 BEACON STREET
CAMBRIDGE MASS

AMOUNT

Detach Here

PLEASE ENCLOSE THIS STUB WITH YOUR REMITTANCE. YOUR CANCELLED CHECK BEARING OUR ENDORSEMENT IS A RECEIPT

MODEL DEPARTMENT STORES
ACCOUNT NO. 50036
PAY LAST AMOUNT IN THIS COLUMN

DATE	ITEM	DEPT. CLERK	CREDITS	CHARGES
Mr 04	SCARF	28032		4 50
Mr 05	HAT	47219		12 00
Mr 05	PAJAMAS	89127		10 50
Mr 08	DRESS	98026		25 00
Mr 09	PR. HOSE	38421		2 95
Mr 12 Cr	SCARF	28032	4 50	
	NET AMOUNT DUE			50 45

Figure 10. Automatically prepared customer's bill

The Transmitter

A number of features of the transmitter have already been described. Referring to figure 5, a telephone handset will be noted resting on top of the device. This is for verbal communication between the transmitter operator (who may be either the sales person or the cashier) and the charge-authorization clerk. The telephone is not used unless there is some question relative to the approval of the credit, and if the authorization clerk desires to converse, she operates a button which causes a light, shown at the left front of the transmitter, to glow. The telephone circuit is already connected by automatic switching, and the transmitter operator has only to lift up the telephone and start talking. In designing the system, it was felt that in the delicate business of passing on the credit standing of the customer, the importance of preserving good will required the flexibility of handling afforded at a distance only by telephonic communication.

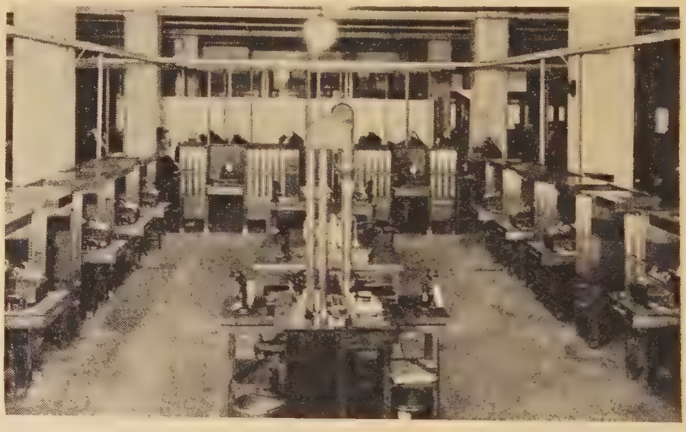


Figure 11. Credit-authorizing room

Electrical interlocks are provided in the transmitter so that failure to put in one of the tokens, or putting in a token in the wrong position, will prevent the transmitter top from locking down when closed, and also prevent the operation of the selector switches and the sending of the record. Two or more transmitters can be connected to a single cable circuit in a "party-wire" relation, and when this is done a transmitter coming on a busy line merely waits until the termination of the transmission period of five seconds before it goes into action. This party-line feature makes it feasible to provide numerous receptacles, analogous to electric-light sockets, into which extra transmitters can be plugged to take care of peak loads occasioned by special sales or other causes. The plug-in feature is obviously useful also in maintenance and repair work.

The transmitter circuits are arranged so as to be inoperable if the wrong number of holes exists or apparently exists in any one of the tokens. Thus a scrap of paper accidentally covering one of the holes of a token would not result in an erroneous record.

The date of sale, which the transmitters stamp on each merchandise tag transmitted, is embossed by small steel stamps, and these have to be changed by hand each day to the new day's date.

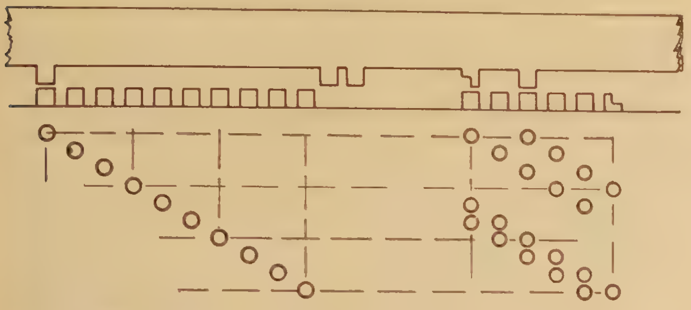


Figure 12. Code bar for punching dual code

Each transmitter contains a circuit which sorts the records and routes the charge sales to the credit authorizing department and the cash sales directly to the recorders.

The Credit Authorizing Machine

The credit authorizing unit, shown in figure 8, receives the record of the account number and amount of sale for a charge purchase. There are five button controls, namely for OK, reject, call back or telephone communication, and two supplementary controls for emergency release and for carriage return. A row of 20 lights in the front of the base is provided to indicate how many calls there are awaiting their turns for being passed upon for authorization. The telephone is at the left of the main unit.

The routing of sales to the credit authorizing machines differs from the indiscriminate method employed for the recorders of selecting any idle machine. Instead, each credit authorizing unit has routed to it by the selector switches only records involving accounts which lie within a specific limited range. The particular unit pictured in figure 8, for example, receives only accounts numbered from 220,000 to 239,999 inclusive, as is indicated by the large numbers just above the row of 20 lights. This routing is accomplished by allowing the first two digits of the customers' charge tokens to control the operation of selector switches which thereupon establish connection to the proper authorizing unit. The purpose of this selection is to reduce the size of the file which has to be provided for and operated by each clerk, thus speeding up the operations and allowing the clerks to become more familiar with their respective lists than would otherwise be possible. There is a considerable saving also in not having to maintain a large number of complete files, and to keep them posted.

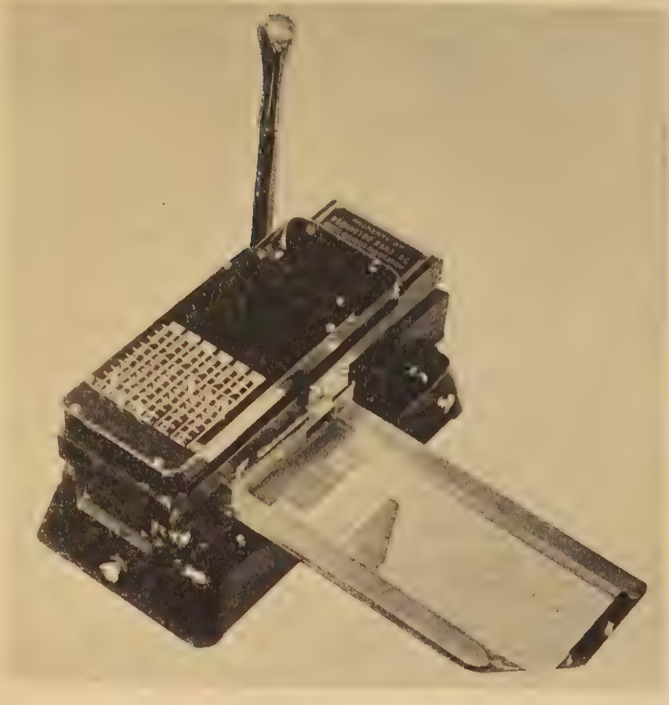


Figure 13. Token punch

A general view of the credit authorizing room in an experimental installation is shown in figure 11. The room contains 15 credit authorizing units around the sides, each with its section of the quick-reference file. In the center of the room are the desks of the supervisors, with telephone and tube communication to the accounts receivable department where more detailed information is available regarding the conditions of the accounts than is available in the quick-reference files.

The Recorder

The recorder is shown in figure 6. It is a combination of a punch adapted for remote-control operation, and a tabulator. A stack of blank cards is kept in the magazine at the front of the machine, as may be seen in the picture. A card is normally always kept in the punching position, between the punches and dies, and if there should by accident be no card there, then an electrical interlock will prevent the particular recorder from being selected by the automatic switching equipment to receive one of the records. In this event a buzzer is also sounded to notify the attendant. As the message comes in, in normal operation, the punching is not done step by step, but instead a set basket is set up with the entire message, and at the end all the punching is done at one stroke. The date of sale is left set up on the set basket all day, so that this does not have to be transmitted. When a sales record card has been punched, the card is automatically fed out of the punching position into a receiving hopper for finished cards at the rear of the machine.

During the time that the message is coming in, an adding and printing unit at the top of the recorder is also being set up. All the data are printed, and totals are carried along of the sales prices and of the identification or serial numbers of the merchandise sold, this latter for the purpose of checking withdrawals of inventory cards from the file, as already mentioned.

Another interlock which has been provided on the recorder cuts it out of circuit unless the traveling carriage, which performs the setting up operation on the set basket, is correctly located at the starting position.

If there should be any lost or mutilated cards, the lists and totals are available to check and to make possible replacement of the lost cards. However, since the cards are produced in the central records room, the chance of losing any of them can be made almost nil.

Coding of Numbers for Transmission

The usual coding of digits on punched cards involves merely punching in the proper one of ten positions numbered from 0 to 9 in each column. The use of such a system for transmitting would require a large number of relays and conductors, and would require a wide price tag, which is considered by retailers as a heavy handicap, because it spoils the appearance and attractiveness of the merchandise. It was therefore decided to adopt the expedient of multiple punching for the merchandise tag, using fewer than ten positions in each column.

It is possible to code the ten digits by the use of a minimum of four positions, using four single-hole and six double-hole codes. However, if a double-hole column had one hole accidentally or purposely covered over, there would result an incorrect transmittal, and this could not be tolerated. With five positions it is possible to have ten combinations of just two holes. However, in working out the transmitter circuits and the coding device in the punch for producing the inventory cards and price tags simultaneously, it was found that a six-position code offered many points of superiority, and this was adopted. The same code was used also for the identification tokens of sales person, customer, and cashier.

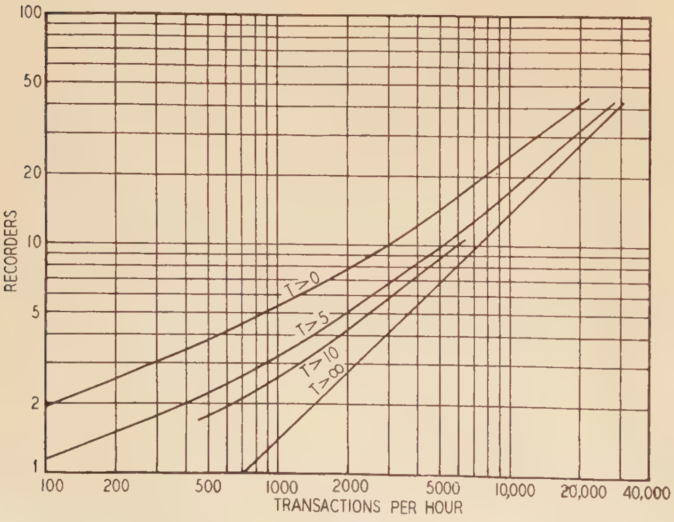


Figure 14. Traffic curves

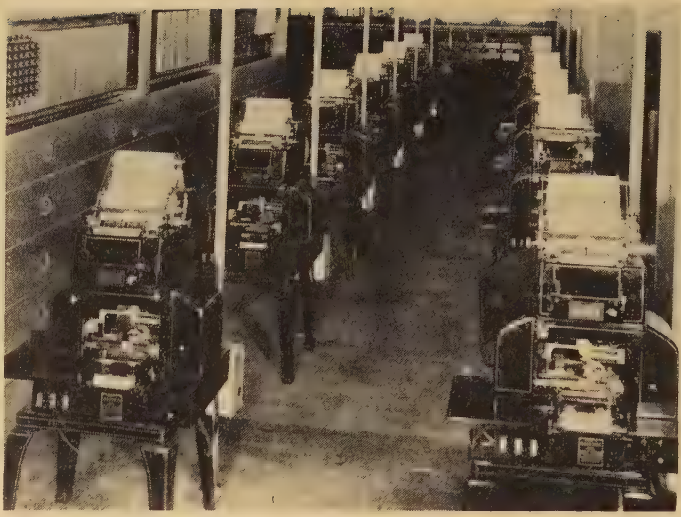


Figure 15. Battery of recorders

In the transmitter, the six-position code made it possible to use three signal wires, each capable of being energized positively or negatively, but only two of them to be energized at one time. This offers 12 combinations, of which only 10 are needed. At the central office, a system of relays decoded the message so that the recording machine received the message over 10 signal wires in a single-hole code.

The Marking Punch

The design of the punch for the simultaneous preparation of the inventory card in single-hole code and the price tag in double-hole code seemed to offer some difficulty, and the first machine for the purpose embodied two separate punches with a set of coding relays connected between them. Subsequent thought, however, evolved a much simpler and more effective mechanical method of coding, which is embodied in the present machine shown in figure 3. This machine has a slide keyboard, and as a slide is moved by hand, a steel rod carrying a lug is moved over the tops of the punches below, in the corresponding column. For the part of the punch which serves to prepare the inventory card there is but a single lug, as shown in the left-hand portion of figure 12. A continuation of the same rod carries four lugs, of which one is partly cut away. The top of one of the punches is also partly cut away to match, and as may be seen by studying the right-hand half of figure 12, the same movement of the same slide and rod will produce a two-hole code in the six-position tag while producing at the same time the usual single-hole code in the inventory card.

The actual punching is accomplished by the lifting of the die-plate after the entire setup has been completed.

Printing units are provided for both inventory card and tag, and the setup is accomplished by but a single operation of the keyboard. The inventory card is imprinted only with characters which are needed in identifying it in the file, and the printing is done at one end so that space-saving vertical filing can be used. This is advantageous also in that the fingering does not wear or soften the long edges which are the ones used in the mechanical feeding of the cards.

In the punch, blank inventory cards are placed in a hopper at the front, and blank price tags at the rear. The finished cards and tags are discharged into hoppers at the middle of the machine. There is an indicator to show when one or the other of the magazines runs empty; a counter for the number of cards and tags; the operation may be controlled for a single card and tag or the machine may be made to turn them out continuously at the rate of 100 per minute.

The Token Punch

For punching the tokens, a small lever-set hand-operated punch, with a code bar similar to that used in the marking punch, is provided. This punch is shown in figure 13. When a token is prepared, a duplicate of the punchings is always made simultaneously on a standard tabulating card and filed away for reference, so that even if an error is made in the punching, it can be discovered and rectified later on.

Traffic Density on Central Records System

The number of transmitters required in the remote-control central records system described depends upon the area and arrangement of the selling space of the store, and the criteria are the convenience and saving of time of the sales employees and the customers, as compared to incremental cost.

The number of recorders required depends only on the peak rate of transactions and the time required for recording each transaction. The time required for each transaction is five seconds.

If each recorder were kept busy continuously, it could handle 12 transactions per minute or 720 transactions per hour. However, it is known that the transactions will not occur evenly throughout the hour, but will occur more or less at random. Sufficient additional transmitters have to be provided to take care of the brief peaks of traffic which will take place owing to this random distribution. It is impossible to avoid some possibility of delay in recording a transaction without providing a recorder for each transmitter, which is economically unfeasible. Some practical compromise must be reached between the two extremes mentioned.

The consideration of traffic density is a problem in the theory of probability similar to trunking and other traffic problems in the telephone industry. A solution applicable to the case at hand has been worked out and charted by E. C. Molina,[2] and a set of curves derived from his article is presented in figure 14. The upper curve of the chart, marked "$T > 0$," shows the relation which exists between the number of transactions per hour and the number of recorders required if the system is to be operated on a basis of one transaction out of every hundred on the average being delayed at all in transmitting. For example, if the rate is 10,000 transactions per hour, then 24 recorders would be required on this basis.

The second curve of the chart, marked "$T > 5$," indicates the relation of the number of transactions per hour and the number of recorders where one transaction out of each 100 would be delayed more than five seconds before transmitting. On this basis there would be required only 17 recorders to take care of 10,000 transactions per hour.

The third curve, marked "$T > 10$," represents the relation existing when one transaction out of 100 will meet with a delay of more than ten seconds before being transmitted.

Naturally, the number of recorders which can be depended on for continuous use will be one or two less than the total number installed, to allow for repairs and maintenance.

The numbers of the different units in the experimental installation were: 250 transmitters, 20 recorders, and 15 credit authorizing units, to handle a peak transaction rate of 9,000 per hour, of which about half were charge transactions. During very busy times, however, charge transactions of very small amount are allowed without specific reference to the credit authorization files.

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2. Application of the Theory of Probability to Telephone Trunking Problems, Edward C. Molina. *Bell System Tech. Jour.*, volume 6, 1927, page 461.

Line-to-Line Faults on A-C Network Feeders

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Synopsis

This paper deals with the magnitude of currents in a secondary a-c network due to a line-to-line fault on the high-voltage feeder, and gives the analysis of the double-unbalance circuit resulting when a network protector fails to open during such a fault, and one of the protector fuses blows. Results of field tests made on an actual network are included.

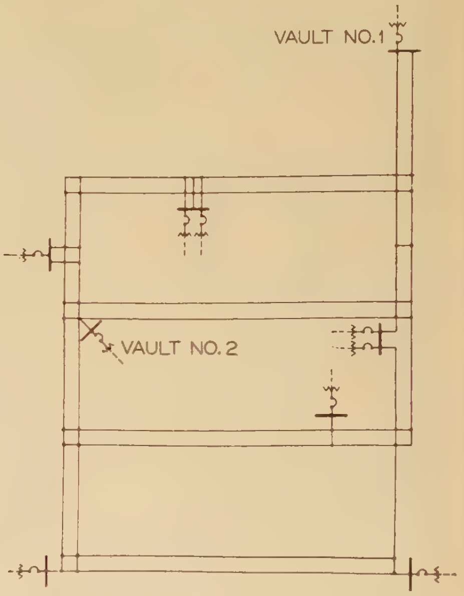
Introduction

IN a low-voltage network, the network protector is designed to open automatically for all faults on the high-voltage feeder supplying the network. In order to provide back-up protection in case a protector fails to open for a feeder fault, fuses are incorporated in the phase leads of the protector. The minimum rating of these fuses is limited to some extent because the fuses should not blow for faults on the low-voltage network. On the Commonwealth Edison Company a-c network, the fuses used on 300-kva transformer banks are rated at 1,500 amperes and those on 500-kva banks at 3,000 amperes.

With the rating of fuses limited by the restriction given above, it is desirable to determine whether or not the various types of primary faults will cause the fuses to blow, in case a protector fails to open for some reason or other. Calculations show that for three-phase faults the magnitude of the fault currents in a typical network, will always be great enough to blow the protector fuses. For line-to-ground faults on the primary feeder, the magnitude of the current through the fuses is well below the fuse rating, because the transformer bank is connected wye-delta. Hence, fuses cannot clear the transformer bank for line-to-ground faults. For line-to-line or two-line-to-ground faults, the analysis of the circuit is more complicated. These types of faults cause unequal currents to flow through the fuses and in many cases only one of the three fuses will blow. The purpose of this paper is to show the results of an investigation made to determine the magnitude of currents in a network for line-to-line faults. This investigation included field tests as well as an analytical study.

Figure 1 is a one-line diagram of a typical network system. The secondary of this system is four-wire, using single-conductor lead-covered cable, the neutral consisting of a copper conductor in parallel with its sheath and the sheaths of the phase cables. Figure 2 shows the flow of currents in the network due to a line-to-line fault on the primary feeder, after the feeder breaker at the station has opened. It will be noted that one fuse carries twice the value of current flowing in the other two fuses. It can be shown that the value of current in the fuse carrying the greatest current is equal in magnitude to the current which would be carried by the fuse for the case of a three-phase fault. In all cases this value of current is great enough to cause the fuse to blow. At the time this fuse blows the remaining two fuses will be intact since they carry only half the value of current. Figure 3 shows the circuit conditions resulting after the first fuse has blown. The current now flows through the two remaining conductors and returns over the neutral path. Since the impedance of the neutral path is comparatively high, the value of current flowing through the two fuses decreases in value after the first fuse blows. This reduced value of current in many cases will not be high enough to blow the two remaining fuses and the transformer bank will not be cleared from the network. If there is more than one transformer bank in a single vault, the reduction in current after the first fuse blows, will not be great enough to prevent the remaining fuses blowing.

Figure 1. Typical low-voltage a-c network



Discussion of Calculations

The solution of the circuit for the conditions shown in figure 2 presents no unusual problem. The fault currents flowing in the circuit of figure 3 were first determined by

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E. L. MICHELSON and NOBLE G. LARSON are both engineers for the Commonwealth Edison Company, Chicago, Ill. The authors wish to thank Professor Edward W. Kimbark, Polytechnic Institute of Brooklyn, for the development of the general equations for the solution of this problem by the method of symmetrical components.

For all numbered references, see list at end of paper.

solving the simultaneous circuit equations based on Kirchhoff's laws. However, it was recognized that this circuit was an interesting case of problems dealing with simulteneous faults on a balanced three-phase system, and could be solved using the method of symmetrical components. The two simultaneous faults in this case are the line-to-line fault on the high-voltage feeder and the open-circuit in the phase in which the low tension fuse is blown. The analysis of the problem using the method of symmetrical components is shown in the appendix. The results obtained using this method checked of course with those obtained using the first method, and the labor required for the solution was considerably shortened.

Table I gives the results of calculations made to determine the value of current flowing through the transformer windings for the case of a line-to-line fault on the high-voltage feeder, after the feeder breaker has opened. The equivalent system behind this transformer which was not cleared has been expressed in terms of an equivalent length of secondary cable between this transformer and the remainder of the system.

Description of Tests

In order to check the accuracy of the assumptions made in these calculations, it was decided to perform tests on a section of the actual a-c secondary network of the Commonwealth Edison Company, shown in figure 1. Tests were made at locations designated as vaults number 1 and number 2, which are supplied from the same high-voltage feeder. The fault was applied by closing two line disconnects to ground at the station, and was initiated and cleared by means of the station oil circuit breaker. At each location two tests were made: first with the *A*-phase fuse removed and second with all fuses in. Table II gives the results of these tests.

Discussion of Test Results

At both test locations, when the fault was applied with the *A*-phase fuse in, only this fuse was blown. The current was reduced to such a value in the remaining phases that these fuses did not blow and the fault was cleared by opening the oil circuit breakers at the station.

The test values checked essentially with the calculated values of current. The results verified the assumption that the effect of the stray ground current was unimportant. It will be noted that the current in the *B* and *C* phases is reduced to approximately 50 per cent of the initial value in both calculated and test results.

Table I. Transformer Secondary Currents for Line-to-Line Feeder Faults

Transformer Kva	Fuse Size (Amp.)	Equivalent Length of Secondary Mains to Banks Supplying Fault Current	Approximate Fault Current: Before first fuse blows A	B	C	After first fuse blows B	C
300	1,500	100 feet	9,900	4,950	4,950	3,150	3,150
300	1,500	200 feet	7,000	3,500	3,500	1,860	1,860
300	1,500	300 feet	5,600	2,800	2,800	1,320	1,360
300	1,500	400 feet	4,500	2,250	2,250	1,020	1,020
500	3,000	100 feet	13,100	6,550	6,550	3,600	3,600
500	3,000	200 feet	8,600	4,300	4,300	2,000	2,000
500	3,000	300 feet	6,300	3,150	3,150	1,400	1,400
500	3,000	400 feet	5,000	2,500	2,500	1,060	1,060

Note: Calculations based on 5 per cent impedance transformers, four single-conductor cables in a duct, 350,000-circular-mil phase cables, and 4/0 neutral cable, the arrangement of conductors assumed to be a square with the conductors as close together as possible. The effect of stray ground current was neglected.

Table II. Results of Tests

	A-Phase Fuse Out	*A*-Phase Fuse In
Vault 1		
A-phase amperes	0	5,680
B-phase amperes	1,500	2,840
C-phase amperes	1,500	2,840
Vault 2		
A-phase amperes	0	10,400
B-phase amperes	2,700	5,200
C-phase amperes	2,700	5,200

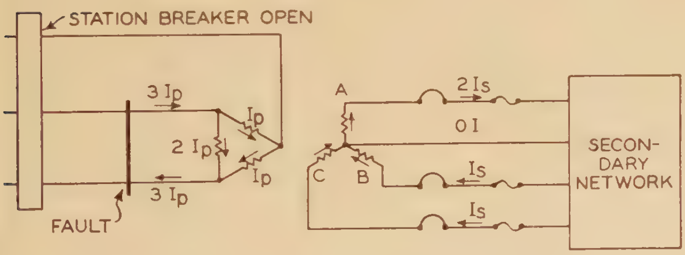

Figure 2. Flow of current in a network due to a line-to-line fault on the primary feeder

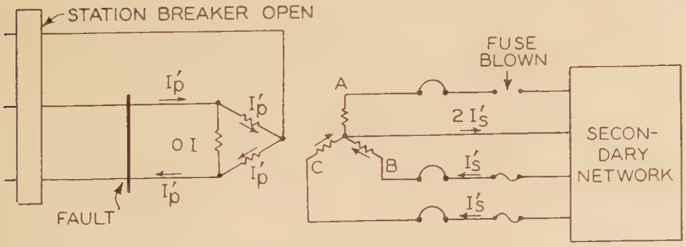

Figure 3. Flow of currents in a network, due to a line-to-line fault on the primary feeder, with the A-phase fuse blown

Appendix—Solution of Circuit of Figure 3, by Method of Symmetrical Components

The circuit of figure 3 can be solved on an a-c calculating board by setting up the sequence networks as shown in figure 4.[1] The open circuit in phase *A* is represented by connecting the three networks in parallel at points *y* and *z* as shown by the dashed lines. The line-to-line fault on phases *B* and *C* is represented by the connection between the positive and negative sequence networks. This connection must be made through one-to-one insulating transformers and because of the delta-wye transformation, the polarity of the

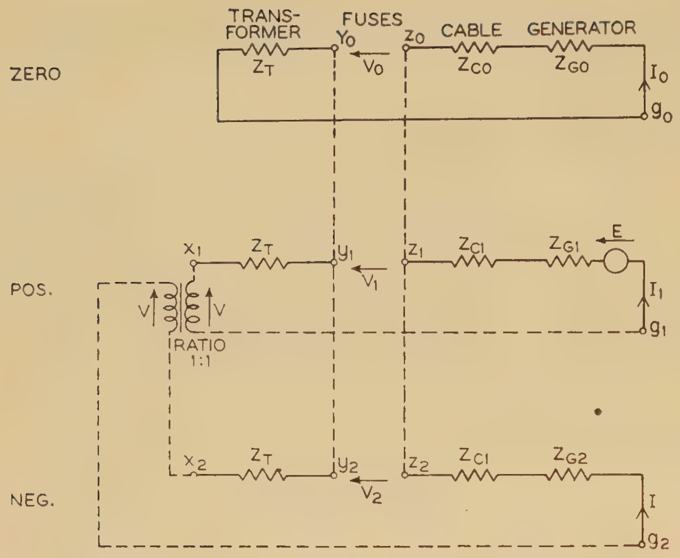

Figure 4. Calculating board set-up for the solution of figure 3 by the method of symmetrical components

insulating transformer must be reversed from the normal method of connection.

The algebraic solution of this circuit is as follows:

Relation between currents:

At open circuit: $I_0 + I_1 + I_2 = 0$ (1)

At short circuit: $I_2 = I_1$ (2)

Equating voltages between points y and z

$$v_0 = v_1 = v_2 \tag{3}$$

or

$$I_0Z_0 = -E + I_1Z_1 + V = I_2Z_2 - V \tag{4}$$

where

V = voltage across the one-to-one transformer.

Z_0, Z_1, Z_2 are the sum of the impedances in the respective networks.

Eliminating I_0, I_2, and V from (4), we find

$$E = I_1(Z_1 + Z_2 + 4Z_0) \tag{5}$$

Let i be the actual value of current flowing through the transformer winding. (I_s' of figure 3.)

$$\begin{aligned} I_1 &= 1/3(I_a + aI_b + a^2I_c) \\ &= 1/3[0 + a(-i) + a^2(-i)] \\ &= 1/3i \end{aligned} \tag{6}$$

Therefore

$$\begin{aligned} E &= i/3(Z_1 + Z_2 + 4Z_0) \\ &= i/3(Z_{g1} + Z_{g2} + 4Z_{g0} + 2Z_{c1} + 4Z_{c0} + 6Z_T) \end{aligned}$$

Where

E = Phase-to-neutral voltage on low-voltage network

and

I_1, I_2, I_0 are the sequence currents in the respective networks.
i = actual current in transformer winding. (See figure 3.)

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1. EXPERIMENTAL ANALYSIS OF DOUBLE UNBALANCES, Edward Kimbark. AIEE TRANSACTIONS, volume 54, 1935, pages 159–65.

2. SIMULTANEOUS FAULTS ON THREE-PHASE SYSTEMS, Edith Clarke. AIEE TRANSACTIONS, volume 50, 1931, pages 914–41.

Lightning Strength of Wood in Power Transmission Structures

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I. Introduction

ALTHOUGH wood has been known to possess the excellent properties of mechanical strength in combination with insulation strength almost since the beginning of the electrical art, its real lightning strength was not generally appreciated until within comparatively recent years. It is true that it was rather extensively used in the past to supply power frequency insulation in treated form alone or with transil oil. For example, wood either solid or laminated has been employed for years in operating rods on oil circuit breakers and in terminal and spacing blocks in transformers. The 60-cycle strength of wood under those conditions has been studied, and although the results were not made available generally, the strength factors had been known with considerable preciseness for some time. In these applications, however, the 60-cycle (i.e., power frequency) strength of wood has been of paramount interest, and the lightning or impulse insulation value of secondary interest, either because the latter was considered comparatively unimportant or because the impulse strength furnished by other insulating members or mediums in the structure was considered sufficient.

The use of wood as supporting structures in transmission and distribution circuits goes back to the beginning of the power distribution art. Here, although it has not been generally realized, the lightning or impulse value of the wood has been utilized consciously or unconsciously and more frequently the latter. The conscious realization of the value of the lightning strength of wood is comparatively recent[1] and goes back little further than 12 years when a comprehensive study of the lightning problem on transmission lines was first undertaken. However, even this late realization of its value was accompanied by very little actual knowledge of the mechanism of such insulation strength. Such conscious realization was first presented in a paper by Melvin[2] giving the impulse insulation characteristics of wood and of wood in combination with insulators. A number of other investigations [3–8] have been described since then, each of which added to our store of knowledge. However, it was felt that certain vital factors had been given little or no study, and that insufficient data were available on the volt-time characteristics of wood in its various forms and in combination with porcelain. Further, little distinction has heretofore been made on the effect of the polarity of the impulse on wood flashover. Again, few test data have been given on actual assemblies of full-fledged transmission lines.

II. Purpose and Scope of Investigation

In the light of the above, the authors undertook a very comprehensive investigation of the lightning strength of wood alone, as used in transmission structures, and in combination with porcelain insulators (pin and suspension) to determine:

(*a*). The volt-time characteristics of the materials in question.

(*b*). Polarity effects, that is, the variation of the characteristics with positive and negative surges.

(*c*). The effect of moisture.

(*d*). The effect of age.

(*e*). The effect of the material employed, such as cedar, pine, and fir.

(*f*). The effect of treatment, particularly creosoting which is coming more and more into common use.

In the course of this investigation actual impulse tests were made on pole structures as used in the past few years on transmission lines, both for 33-kv and 66-kv service. Here tests were carried out on actual pole-line assemblies as they existed before and after structural changes were made to take advantage of the wood impulse insulation strength.

III. Test Equipment and Procedure

All of the flashover studies were carried out in the Ohio Brass High-Voltage Laboratory at Barberton with surges applied from the 3,000,000-volt impulse generator. The standard $1^1/_2$ by 40-microsecond wave was used, thereby allowing comparison with the impulse data of other insulation for the purpose of system co-ordination. Both positive and negative surges were applied in practically all cases, and oscillograph records were secured of the resultant voltage waves. From these oscillograms the volt and time data were taken for plotting the various curves here given.

Figure 1 illustrates some of the typical oscillograms, with impulses applied ranging from full waves to waves resulting in flashover of the structure under test in 1.8 microseconds. The nesting of the curves, as shown, is a very effective method of accurately correlating the records as the test work progresses, as well as greatly reducing the time otherwise required in changing film.

All flashover values were corrected to standard air density conditions. Inasmuch as no humidity correction factor for wood has been established as yet, no corrections were made for this atmospheric factor. To make possible

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[1] For all numbered references, see list at end of paper.

a proper comparison therefore of wood, porcelain, and air-flashover values, the latter two were corrected to the humidity at which the wood specimens were tested.

The wood crossarms studied consisted of typical specimens of untreated and creosote dipped Douglas fir, and creosote impregnated pine. Crossarm sizes varied from three and one-half by four and one-half inch to six by eight-inch cross section. In most cases new and old specimens were used, the latter having seen varying years of field service up to about ten years. For pole members, red cedar and creosoted pine were used, new and similar old specimens being chosen here as well.

Various lengths of individual wood specimens were flashed over in order to determine the impulse strength furnished by each. Braided copper bands which could be moved along the wood were employed as electrodes, and the wood lengths tested varied from a few inches up to eight feet. Voltage from the impulse generator was always applied to one band while the other band was grounded. In each case the wood specimen was suspended at a distance from ground equal to several times the length of gap being tested, in order to allow as little interference as possible with the field surrounding the wood gap. In securing flashover data upon successive lengths of the same specimen, care was taken to avoid wood surfaces which were too badly splintered from previous discharges. A certain amount of splintering had no appreciable effect upon the flashover voltages, although badly shattered members showed some reduction of insulation strength.

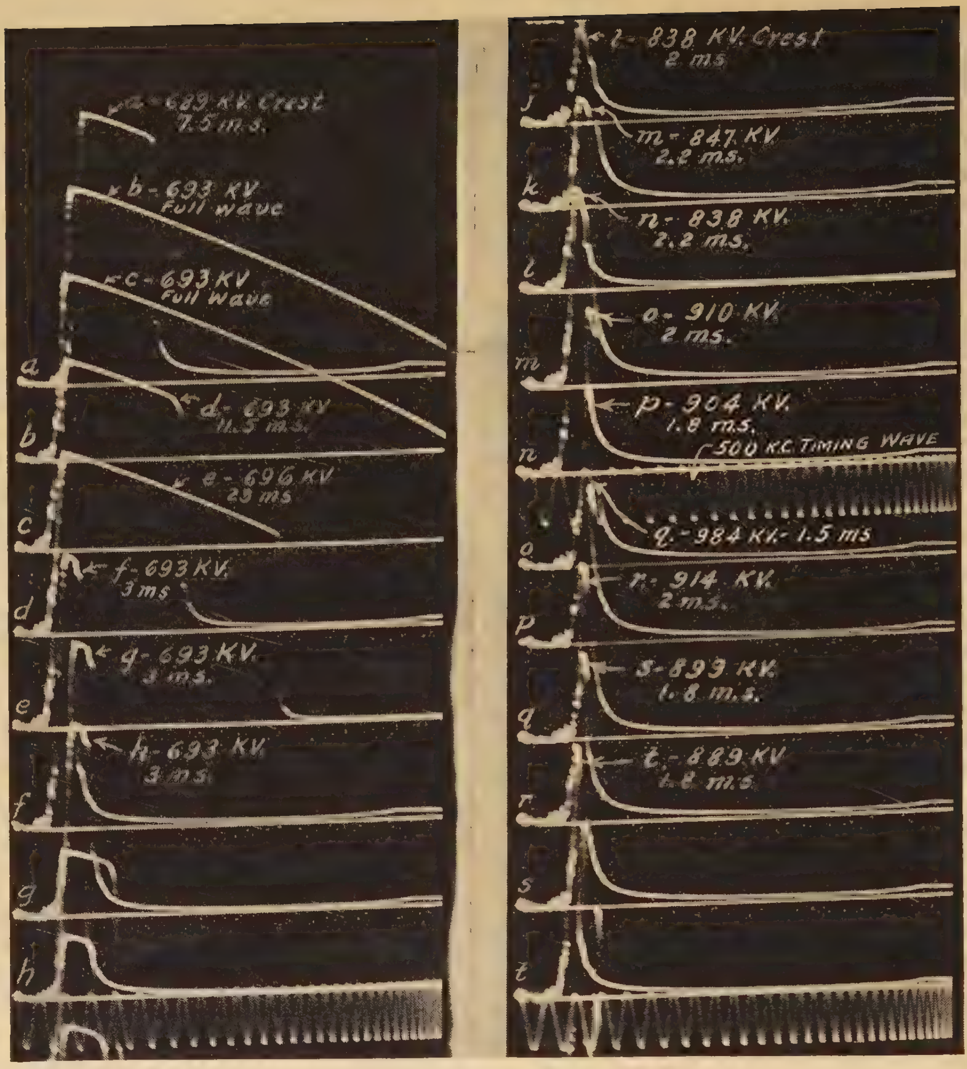


Figure 1. Typical oscillograms of impulse tests on wood and wood-porcelain structures. The above tests were made on three 5- by 10-inch suspension insulators plus four feet of creosoted pine crossarms with 1½x40 microsecond positive polarity

Tests were made on combinations of wood and porcelain to determine the total insulation strength afforded. In these studies varying sizes of pin-type insulators and lengths of suspension strings were used. These were mounted on the several types of crossarms noted above and flashover made with different lengths of wood in series with the insulator units. In this way the effect of various combinations of porcelain and wood insulation were investigated. An effort was made to confine the tests to combinations which were typical of field installations. Figure 2 illustrates such a typical specimen on test.

IV. Test Results—Structure Members

1. CROSSARMS

Eleven crossarm specimens of the three types of wood previously noted were given impulse flashover tests, and volt-time curves plotted from the oscillograph data. Figure 3 illustrates two sets of such curves for 12-inch and 36-inch wood gaps. Corresponding NEMA rod-gap curves are also given in order to show the comparative volt-time characteristics of air gaps. In figure 4 are given the minimum and two-microsecond flashover values for various lengths of wood arms.

These arms were of various cross sections. It being quite apparent from the test data that cross section is a vital factor in the impulse flashover value of an arm an effort was made to determine the effect of this factor upon impulse insulation strength. Accordingly, new curves were plotted of flashover voltage against cross-sectional area. Figure 5 (*A* and *B*) shows such curves for creosoted and untreated fir, and creosoted pine. It will be noted that these are practically straight lines with flashover

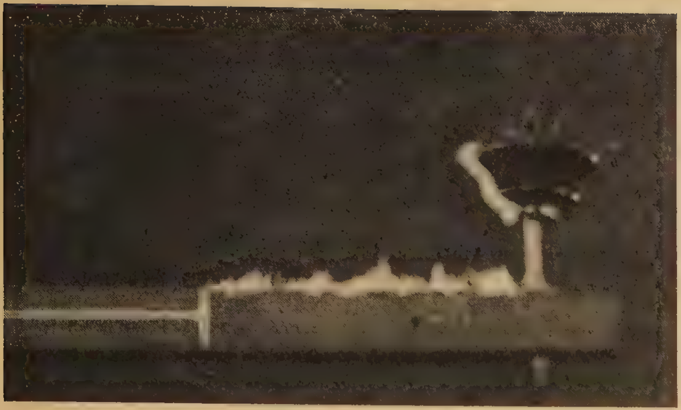


Figure 2. Typical impulse flashover in the laboratory of 33-kv pin insulator plus two feet of creosoted Douglas fir crossarm

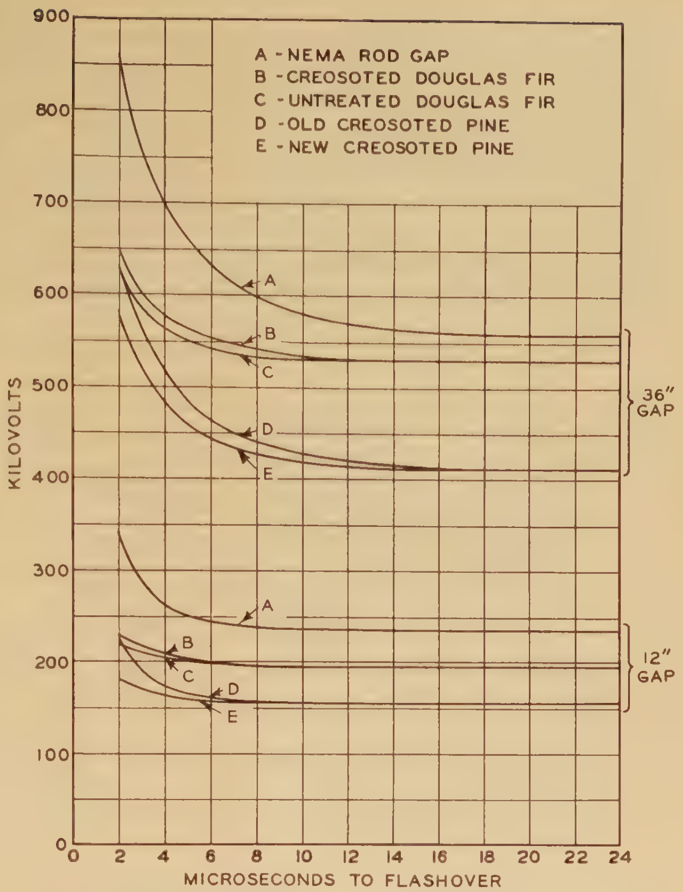


Figure 3. Impulse flashover of wood crossarms of 20-square-inch cross section; positive polarity

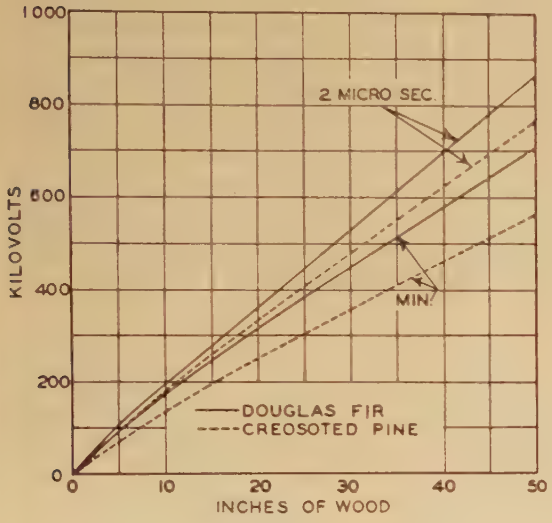
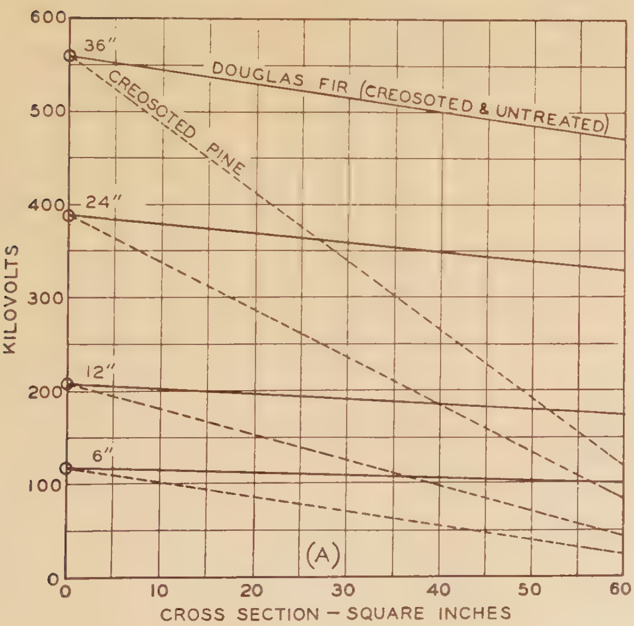


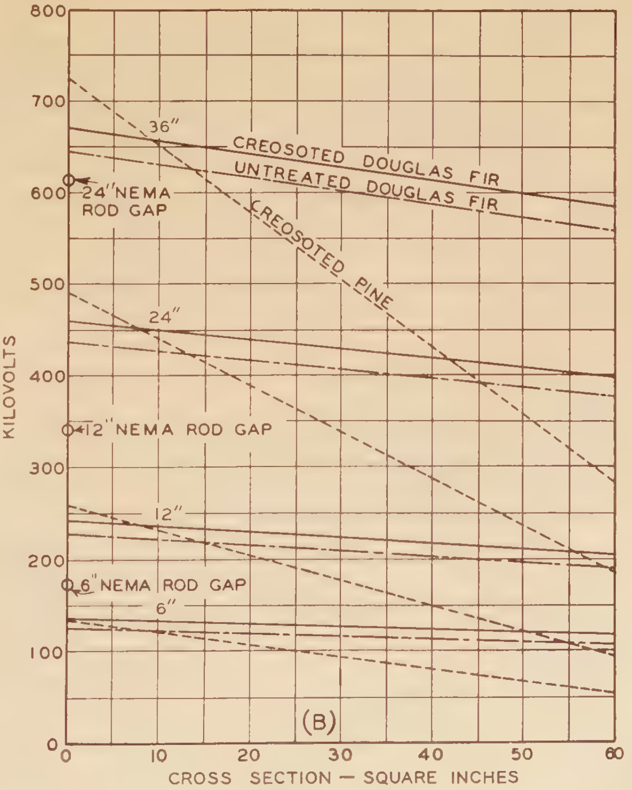
Figure 4 (left). Impulse flashover of Douglas fir and creosoted pine crossarms. Average of positive and negative average values. Two-microsecond and minimum values only are given

Figure 5. Effect of wood cross section on impulse flashover of fir and creosoted pine crossarms

A—Positive polarity; minimum flashover

B—Positive polarity; 2 microsecond flashover





decreasing with increased cross section. Most of these data were obtained at a humidity of 0.4 inch of mercury-vapor pressure. The NEMA rod-gap flashover values for this humidity were selected and plotted for zero cross section of wood. It will be noted that at minimum flashover these air-gap values lie on the wood flashover curves. For the 2-microsecond points they lie above the wood curves, indicating that the air gap has a steeper volt-time curve, and therefore greater time lag than the corresponding wood gap. This decrease of flashover strength with increase of cross section is probably due to the fact that there is a greater chance of weaker flashover paths, the larger the wood cross section. Obviously, too, the larger members have more chance of retaining internal moisture and other impurities which lessen the insulation strength. It will be noted, too, that the steepness of the curves is greatly influenced by the class of wood and treatment. The rapid decrease of strength in the case of the pine arms was unexpected and further work is to be done to check this.

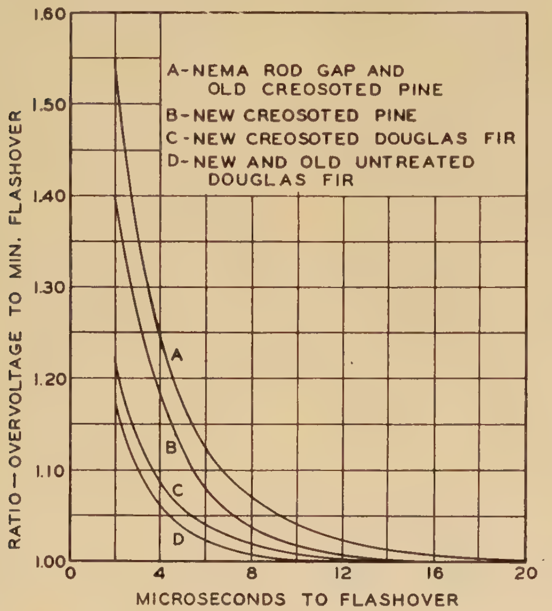


Figure 6. Volt-time characteristics of 36-inch crossarms; 20-square-inch cross section; of various woods; positive polarity

In figure 6 there is plotted a form of volt-time curve expressing ratios of overvoltage to minimum flashover in order to permit a direct comparison of the insulating properties of the various materials involved. It will be noted that the rod-gap curve is the highest one of the group. Its characteristics are approached only by the creosoted pine members, the old pine having been found to lie approximately on the air-gap curve. These curves also illustrate why the minimum flashover values of the rod gap on figure 5*A* coincide with the zero cross sections of wood, whereas the 2-microsecond values do not. The corresponding true volt-time curves of any of the materials shown obviously can be plotted by using the proper minimum flashover values and multiplying by the corresponding ratios shown in figure 6.

2. Wood Poles

In figure 7 there are plotted the minimum flashover voltage values of various lengths of pine and cedar poles. In order to illustrate the time-lag characteristics of these members, volt-time curves of the eight-foot sections have been plotted in figure 8. On this figure are included cor-

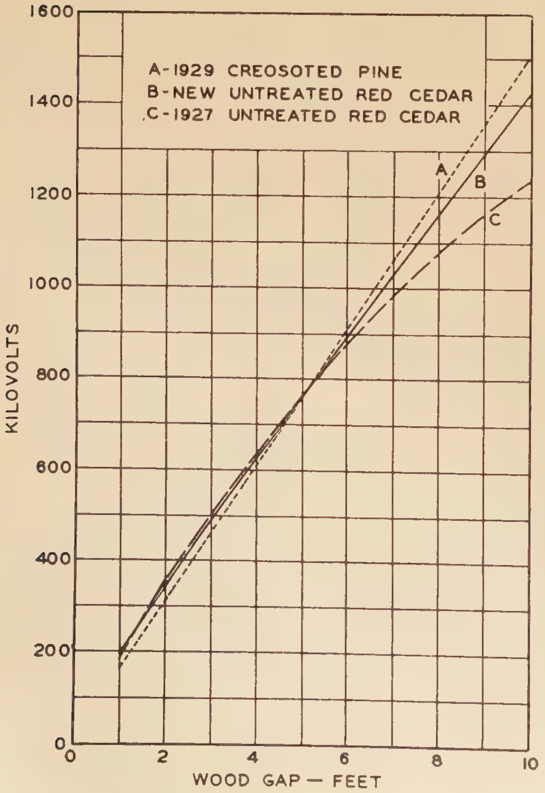
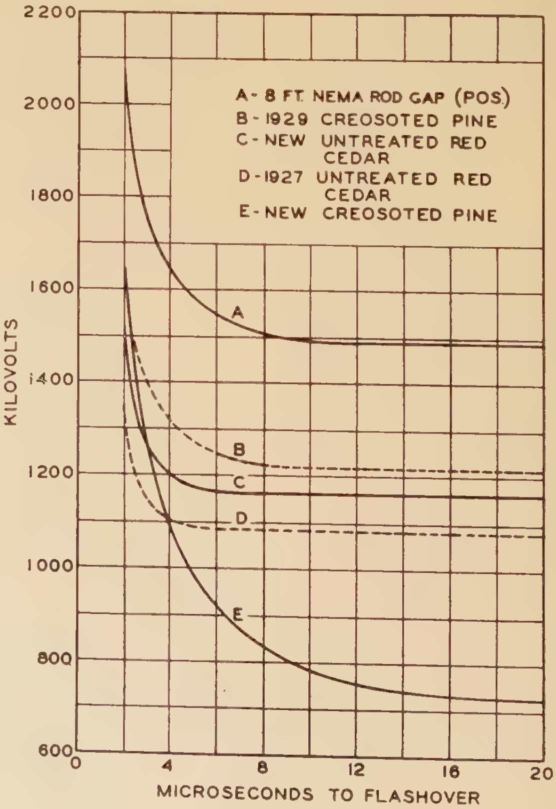


Figure 7 (left). Impulse flashover characteristics of wood poles; minimum positive polarity

Figure 8 (right). Volt-time characteristics of eight-foot wood-pole sections (positive and negative values are approximately equal)



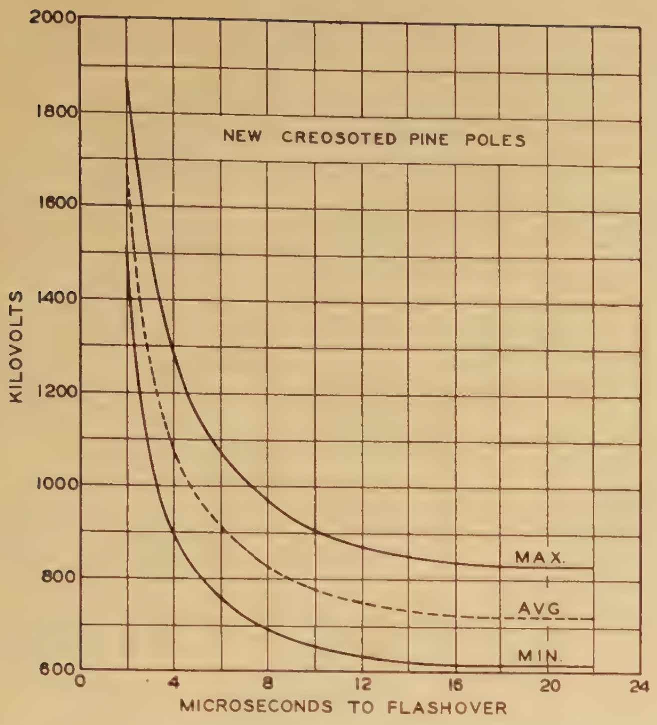


Figure 9. Variation in impulse flashover characteristics of wood poles; eight-foot length; positive wave (positive and negative values approximately equal)

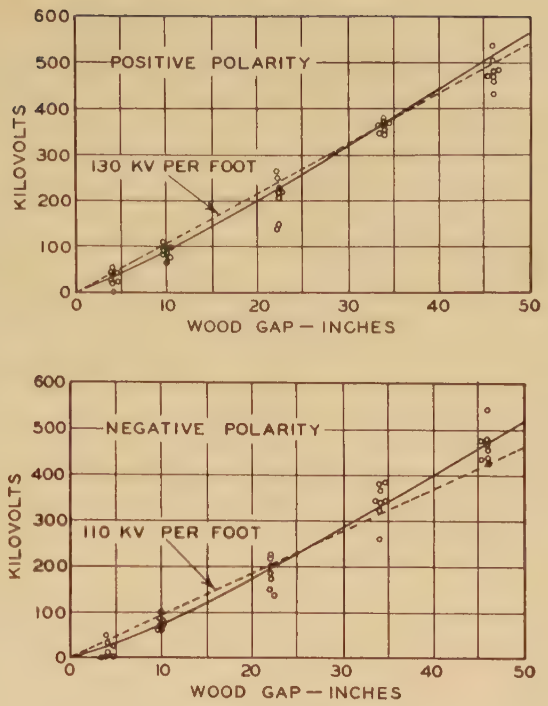
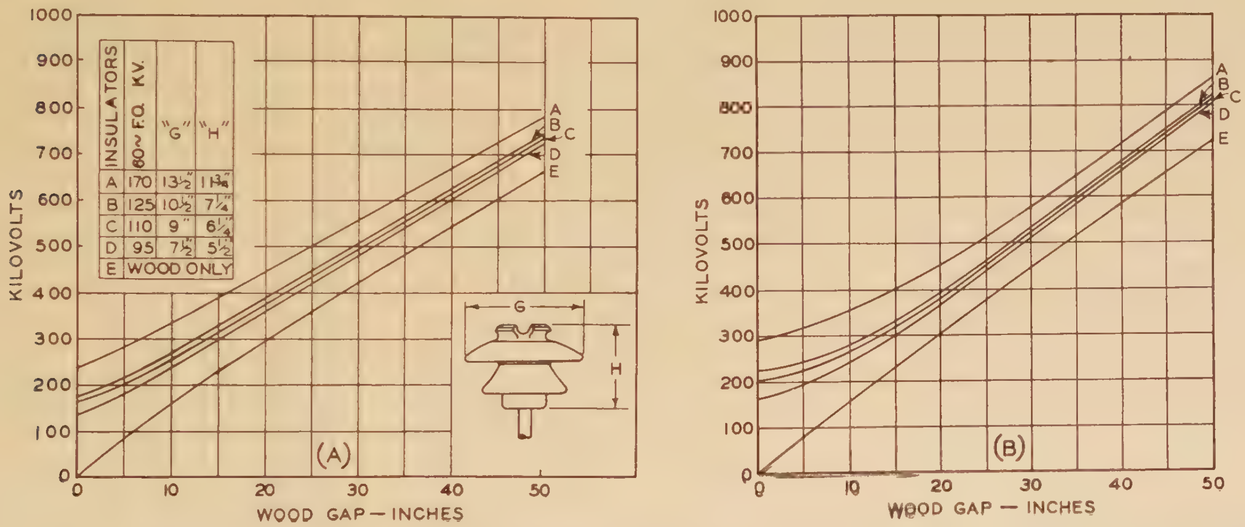


Figure 10C. Impulse insulation added to pin insulator by creosoted or untreated fir crossarm; minimum wave values. Insulators used same as shown in table of figure 10A



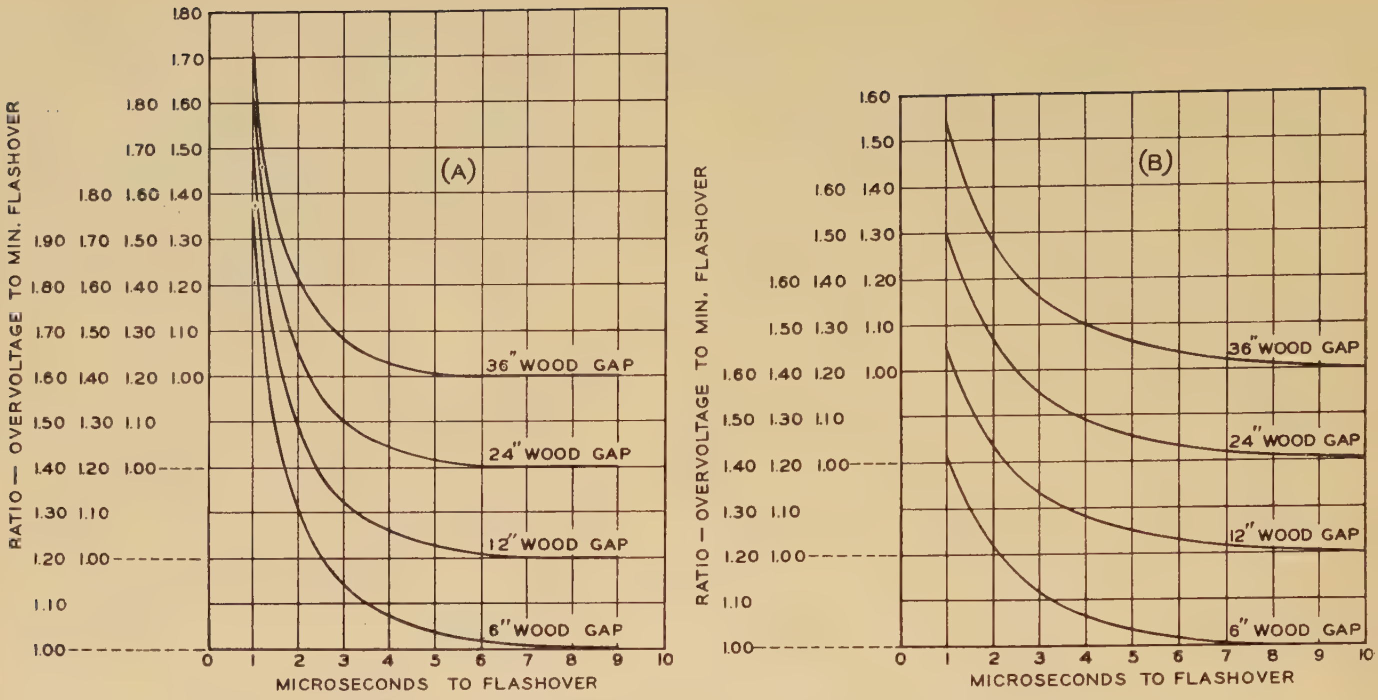
Figures 10A and 10B. Impulse flashover characteristics of pin insulators plus creosoted fir crossarm; minimum flashover

A—Positive polarity *B*—Negative polarity

responding spacings of rod gap and newly creosoted pine poles. It will be noted that the latter two represent the upper and lower limits respectively of insulation strength. A further examination will show that at minimum wave values, the insulation value of the plain rod gap is as much higher than the older wood members as the latter are higher than the newly creosoted pine poles. The last were tested within a week or so after leaving the treating plant, and it is felt that their reduced insulating properties were due largely to the moisture retained within them. Over 50 of these poles were used and numerous tests made. In figure 9 is plotted the band within which these values fell. This is typical of the spread in the test data obtained in some wood tests. It is pertinent, however, to note that this spread was found to be somewhat greater with the new, moisture-laden poles than was the case with the older and drier specimens. This lower insulation strength of new, undried poles would seem to account for the more frequent flashover and splitting often encountered during the first year's operation of newly creosoted poles, as compared to their performance after several years.

3. Wood Plus Pin Insulators

Figure 10 (*A* and *B*) shows data obtained on combinations of several pin-type insulators, and various lengths



Figures 11A and 11B. Impulse flashover characteristics of pin insulators plus fir crossarms

A—Positive polarity *B*—Negative polarity

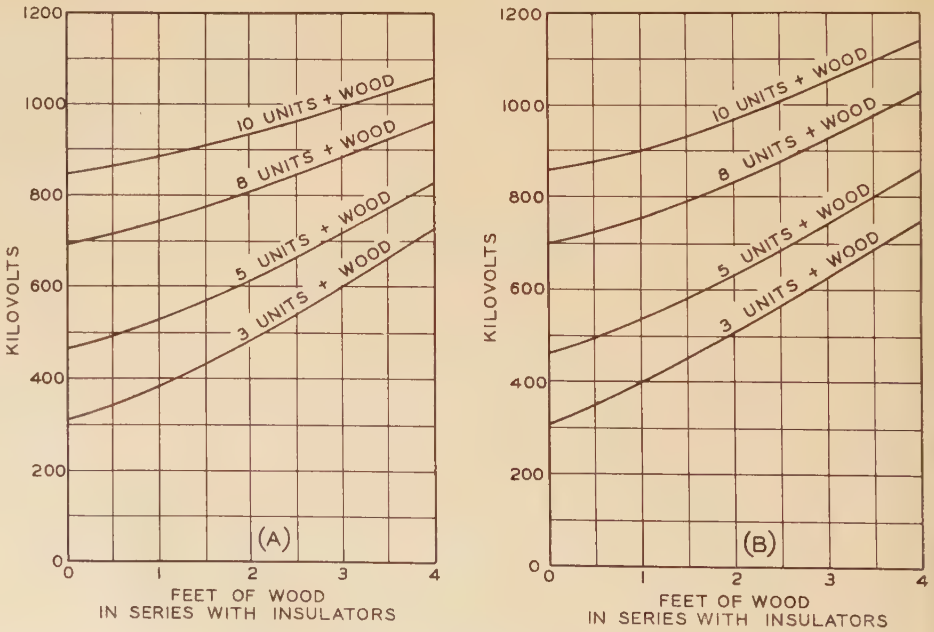
of wood arm. The curves for "wood only" show the insulation supplied by the wood alone. At the zero wood gap points are plotted the corresponding flashover voltages for the insulators only. It will be noted that for lengths of wood arm beyond approximately 10 to 12 inches the curves become straight lines and the insulation strengths increase almost in proportion to the lengths of wood added. In fact a composite plot of data from tests on the several forms of wood and sizes of insulators indicated that the amount of insulation added by the wood is almost proportional to the length of arm regardless of the insulator used or the wood treatment. This is shown in figure 10*C*. In the case of the positive surges the curve slope shows an insulation increment of about 130 kv per foot of wood and for the negative surges about 110 kv per foot, these values representing minimum flashover values.

In figure 11 (*A* and *B*) are given the overvoltage characteristics of pin insulators on wood arms. These curves are derived from data taken on both creosoted and untreated arms as it was found that the wood treatment had comparatively little effect upon the resultant insulation strengths of the arm and insulator combinations tested.

4. Wood Plus Suspension Insulators

The flashover data obtained with suspension insulators on wood arms were analyzed in the same manner as the data on pin insulators. Figure 12 (*A* and *B*) gives the positive and negative flashover voltage of various lengths of fir arms in series with suspension units.

To show the insulation strength added to suspension insulators by wood crossarms the curves of figure 13 were



Figures 12A and 12B. Impulse flashover characteristics of 5-inch by 10-inch suspension insulators plus fir crossarm; minimum flashover

A—Positive polarity *B*—Negative polarity

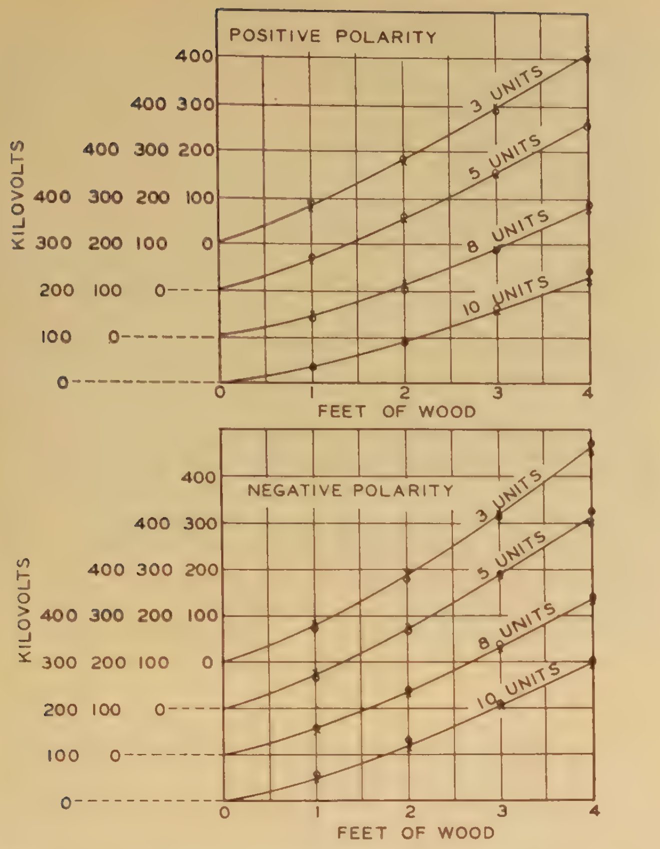


Figure 13. Impulse insulation added to suspension insulators by crossarms—minimum wave values

o—Creosoted pine
x—Untreated and creosoted fir

Figures 14A and 14B. Impulse flashover characteristics of suspension insulators plus fir crossarm, one to four feet long

A—Positive polarity
B—Negative polarity

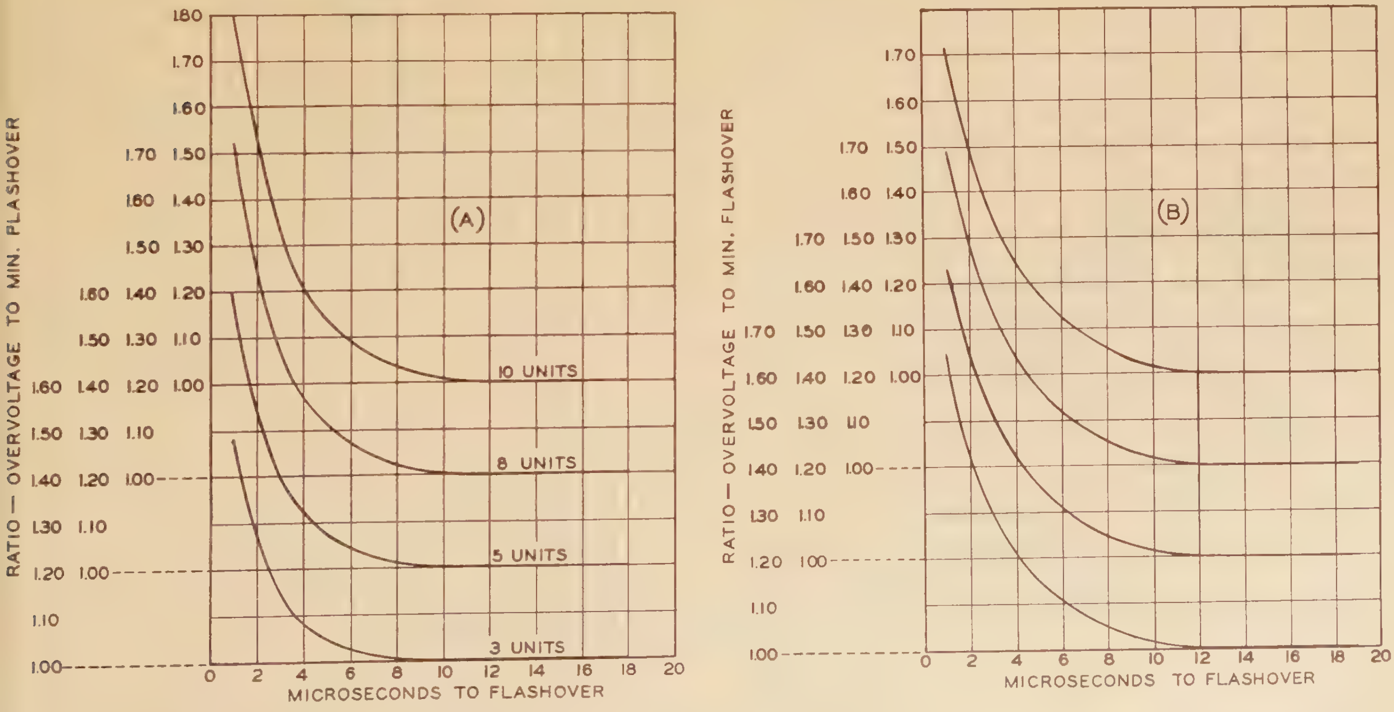


Table I. Comparison of Calculated and Measured Impulse Flashover of 33-Kv Wood Pole (See Figure 15)

Member	Location	Min. Wave		At 2 Ms.	
		Pos.	Neg.	Pos.	Neg.
Case 1. Phase-to-ground flashover in kv (wood values from figures 4 and 6)					
Insulator	(*a*)	175	225	236	248
$3^1/_2''$ Wood	(*b*)	65	65	85	85
Sum	(*a*)(*b*)	240	290	321	333
Measured	(*a*)(*b*)	214	256	300	276
Ratio—Measured/sum		0.89	0.88	0.93	0.83
Case 2. Phase-to-phase flashover—horizontal in kv (wood values from Figures 4 and 6)					
Insulator	(*a*)	175	225	236	248
$3^1/_2''$ Wood	(*b*)	65	65	85	85
$3^1/_2''$ Wood	(*c*)	65	65	85	85
Insulator	(*d*)	225	175	248	236
Sum	(*a*)(*b*)(*c*)(*d*)	530	530	654	654
Measured	(*a*)(*b*)(*c*)(*d*)	395	420	500	540
Ratio—Measured/sum		0.74	0.79	0.76	0.82
Case 2A. Same as (2) but calculated from combinations of insulation plus wood F.O. in Kv (wood values from figures 10*C*, 11*A*, and 11*B*)					
Insulation and wood	(*a*)(*b*)	205	245	265	295
Insulation and wood	(*c*)(*d*)	245	205	290	265
Sum	(*a*)(*b*)(*c*)(*d*)	450	450	560	560
Measured	(*a*)(*b*)(*c*)(*d*)	395	420	500	540
Ratio—Measured/sum		0.88	0.93	0.89	0.96

developed for both positive and negative impulses. It will be noted that the wood adds more insulation to the shorter string lengths. This is probably due to the voltage distribution between the porcelain and wood insulations in series, as affected by their relative capacities, a point which is being given further study. Another interesting factor developed was that although fir arms have higher flashover values than creosoted pine arms when alone, there seems to be little difference between the two when assembled with insulators. This is clearly indicated in figure 13. The wood values in these curves may be used with suspension units of any of the standard dimensions.

The time-lag characteristics of typical suspension insulators on wood arms from one to four feet long are given in figure 14 (*A* and *B*).

V. Test Results—Complete Structures

Laboratory studies were made of typical transmission line structures in order to determine how well their insulating properties could be calculated from the flashover values of the component parts, these latter values being secured from data curves such as given in the previous figures. Figure 15 shows one of the 33-kv structures, (*A*) being the arrangement before, and (*B*) the arrangement after, construction changes had been made to gain lightning insulation.

Table I gives the data obtained from such an analysis and test. Separate data corresponding to the various parts or members of the structure analyzed and tested are given. In each case the values given for the individual members, such as insulators, wood sections, and air gaps, are from the particular flashover voltage curve corresponding to that member. The stated sums of these values are the arithmetical sums and these are compared by ratio with the actual measured values secured by test on the particular group of members.

In the first case analyzed in table I namely that of a phase-to-ground flashover on a 33-kv insulator and arm combination, the ratios of the sums of the voltages of the separate members to the measured voltage of the combination is seen to be around 0.90 or 90 per cent. This ratio was found to be about the order of magnitude generally obtained in the case where the sum of the flashover voltages

Figure 15. 33-kv structure before and after redesign to increase its impulse strength. Note the use of wood crossarm braces, and the down lead offset from the pole in B

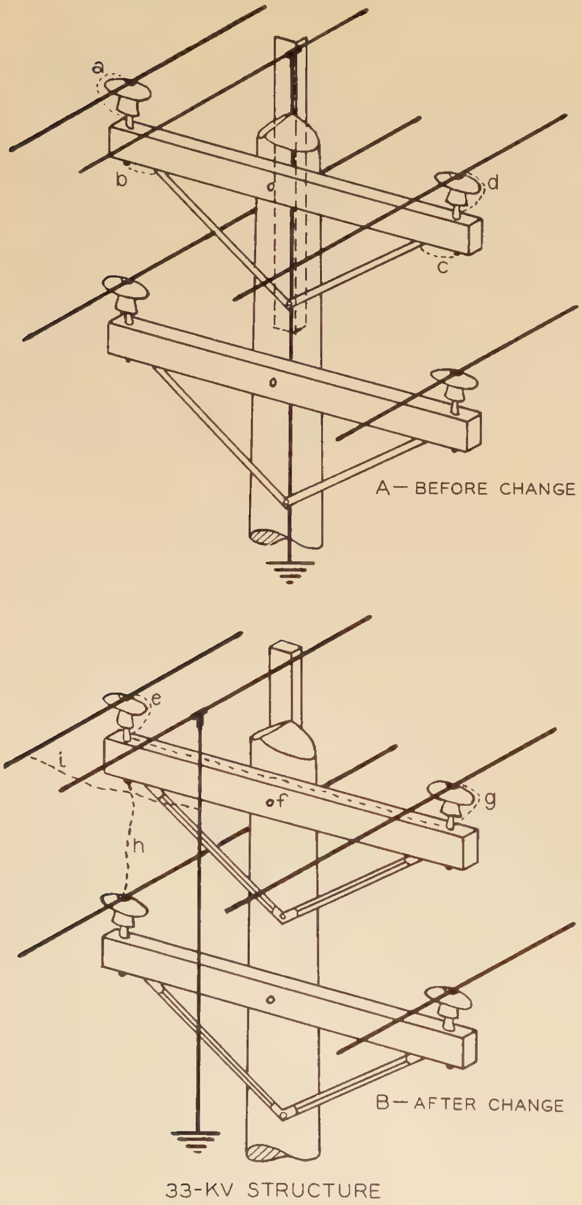
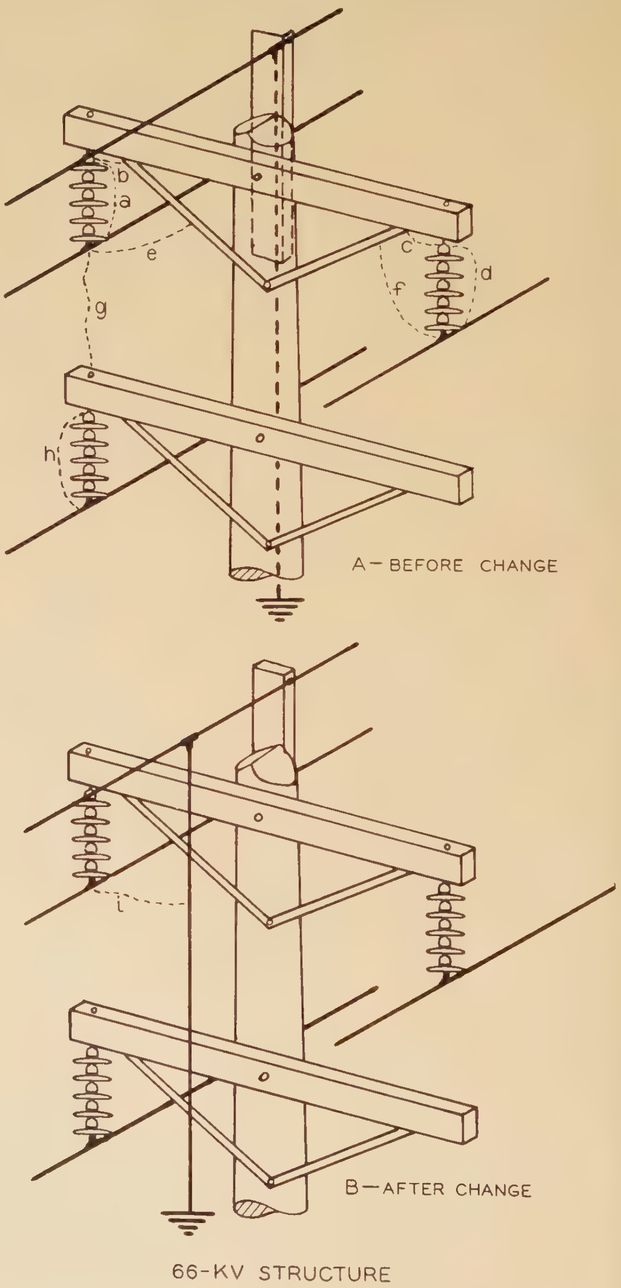


Figure 16. 66-kv structure before and after changes in design to better utilize impulse insulation of wood. The down lead has been offset, but the metal braces retained



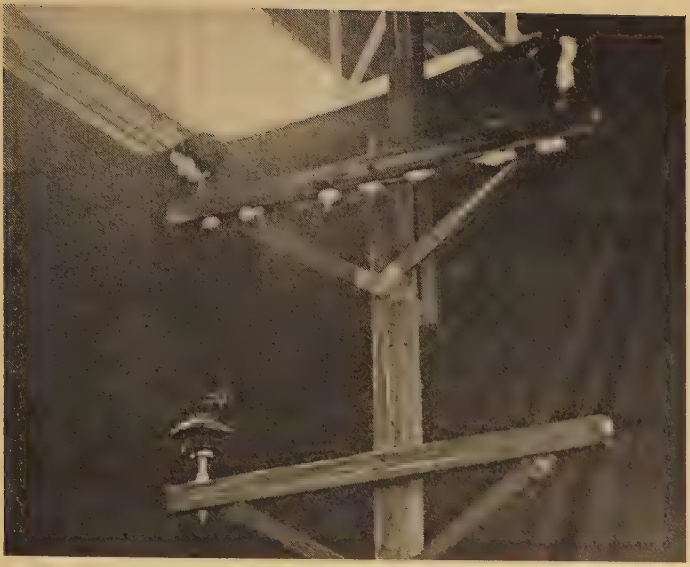


Figure 17. 33-kv wood-pole structure being impulse tested in the laboratory. Flashover is taking place across the top crossarm, line to line

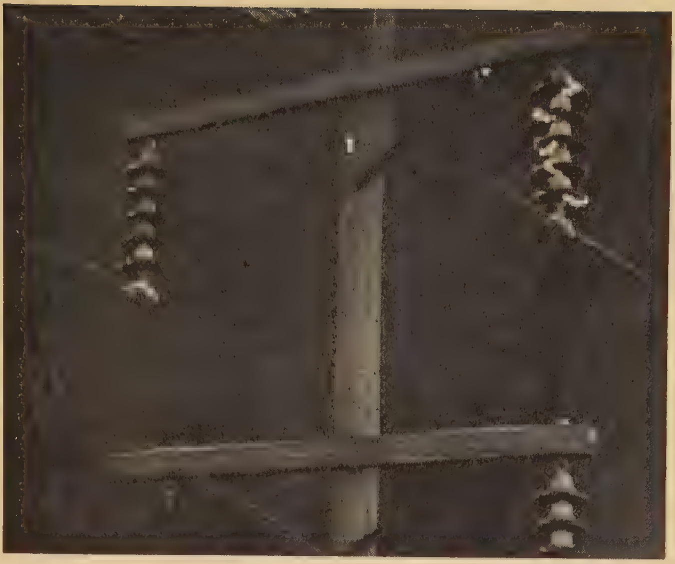


Figure 18. 66-kv wood-pole structure flashing over on laboratory test from conductor to down lead by way of the crossarm, brace, and wood pole

of two single members or groups of members are compared with the actual flashover value of the group. In the case where four single members or groups of members are involved, a ratio of about 0.75 or 75 per cent was found to hold. This is brought out in the second case of table I, where the sums of the individual flashover values of two insulators and two sections of wood are compared with the test values of the combination.

On the other hand if the four members involved, namely, two insulators and two wood sections, are grouped in pairs, each consisting of an insulator and a wood section, values may be chosen from figures 10*C*, 11*A*, and 11*B*. This results in a ratio of approximately 0.90 or 90 per cent as noted for case 2*A*.

In adding these phase-to-phase values, it will be noted that values of opposite polarity are selected for the insulators in each summation. The reason for this is that when one conductor is energized and the other grounded the insulator supporting the energized conductor experiences an electrostatic field of opposite polarity from that of the insulator supporting the grounded conductor. In all tests made phase-to-phase, the down lead was ungrounded.

Table II. Impulse Flashover Characteristics of Wood Structures; Ratios of Measured to Calculated Values by Summation of Elements

Ref.	Structure Type	Flashover Path	No. of Elements	Min. Wave Pos.	Min. Wave Neg.	At 2 Ms. Pos.	At 2 Ms. Neg.
1	33 kv	Phase to Ground Wire	2	0.89	0.88	0.93	0.83
2	33 kv	Phase to Phase (Hor.)	4	0.74	0.79	0.76	0.82
3	33 kv	Phase to Phase (Hor.)	2*	0.88	0.93	0.89	0.96
4	33 kv	Phase to Phase (Hor.)	4	0.74	0.72	0.84	0.68
5	33 kv	Phase to Phase (Hor.)	2*	0.95	0.93	1.06	0.85
6	33 kv	Phase to Phase (Vert.)	2	0.96	0.85	0.94	0.85
7	33 kv	Ph. to Grd. Wire	1	0.94	0.82	1.02	0.96
8	66 kv	Ph. to Grd. Wire	2	0.87	0.87	0.91	0.91
9	66 kv	Ph. to Ph. (Hor.)	4	0.72	0.72	0.82	0.82
10	66 kv	Ph. to Ph. (Hor.)	2*	0.92	0.92	1.02	1.02
11	66 kv	Ph. to Ph. (Hor.)	2	0.86	0.86	0.87	0.87
12	66 kv	Ph. to Ph. (Vert.)	2	0.89	0.84	1.00	0.91
13	66 kv	Ph. to Grd. Wire	1	0.93	0.88	0.95	0.90
		Average	1	0.94	0.85	0.99	0.93
			2	0.89	0.86	0.93	0.83
			2*	0.92	0.92	0.96	0.95
			4	0.75	0.75	0.81	0.77

* Each element consisted of porcelain and wood or air.

Figure 16 (*A* and *B*) illustrates the 66-kv structure where the down lead has been moved from the pole to secure increased insulation. Figure 17 shows the 33-kv structure flashing phase-to-phase on test. Figure 18 shows a similar flashover, phase-to-ground, on the 66-kv structure.

In table II the ratios of measured to calculated impulse flashovers for both 33-kv and 66-kv structures are given. It will be noted that where the flashover path is across only one or two elements of insulation the ratio is around 0.90, and where four elements are involved it is around 0.75.

The flashover values taken for the air paths in the calculations are those from the flashover data secured on the so-called "standard rod gap." As this gap is usually mounted rather close to ground, it has a distinct polarity characteristic, that is, the negative flashover value is appreciably above the positive. However, on transmission structures, air gaps are often rather far from large grounded structures, so that there is little to unbalance their electrostatic fields and cause appreciable differences between the positive and negative flashover voltages. For this reason it is felt that the ratio in these tables should be somewhat lower where air gaps involve an appreciable part of the total insulator path.

Figures 19 (*A* and *B*) and 20 (*A* and *B*) were developed to show the accuracy with which volt-time curves of complete structures can be calculated from the flashover voltage curves of the component parts. In these figures, two sets of curves are shown, one the actual measured curves, and the other the estimated curves secured by adding component voltages and multiplying by 90 per cent or 75 per cent dependent upon whether two or more figures were added, as discussed above. It will be noted that the two sets of curves agree rather well.

These curves also show the increased impulse strength obtained by the change in construction, that is, by using wood braces and offset down lead on the 33-kv structure, and by offsetting the down lead alone on the 66-kv structure.

A short series of wet tests on wood structures was also made. These tests are not reported here in detail. They apparently indicate, however, that the impulse flashover voltages would be little affected at short-time lags (less than 4 microseconds), but that at long-time lags and at minimum flashover, appreciable reductions might be experienced. In some cases the flashover voltages were decreased 50 per cent. Additional tests are being made on structures under wet conditions to obtain more complete data on their flashover characteristics.

VI. Conclusions

As a result of these tests comprising the application of some 4,000 to 5,000 individual impulse voltages on wood alone and in combination with porcelain, both on individual members and actual structures, the following conclusions seem to be justified:

1. Wood has a definite and sound field of application in supplying insulation against lightning voltages on wood structures such as are commonly used for transmission and distribution circuits.

2. The wood in crossarms can be taken advantage of to supply appreciable impulse insulation on lines using both pin insulators, where the impulse insulation is comparatively low, and on suspension insulators in the higher-voltage ranges where the insulator strings normally have a relatively high insulation strength.

Impulse insulation supplied by wood crossarms in combination with pin insulators is in the order of 110 to 130 kv per foot for minimum waves and somewhat higher for short-time lags.

Tests on individual members as well as complete structures indicate that the flashover path changes as the overvoltage increases. For example, in some cases, flashovers appearing through air for minimum waves will take a path across the wood as the overvoltage increases due to the faster rising volt-time characteristic of the air gap breakdown.

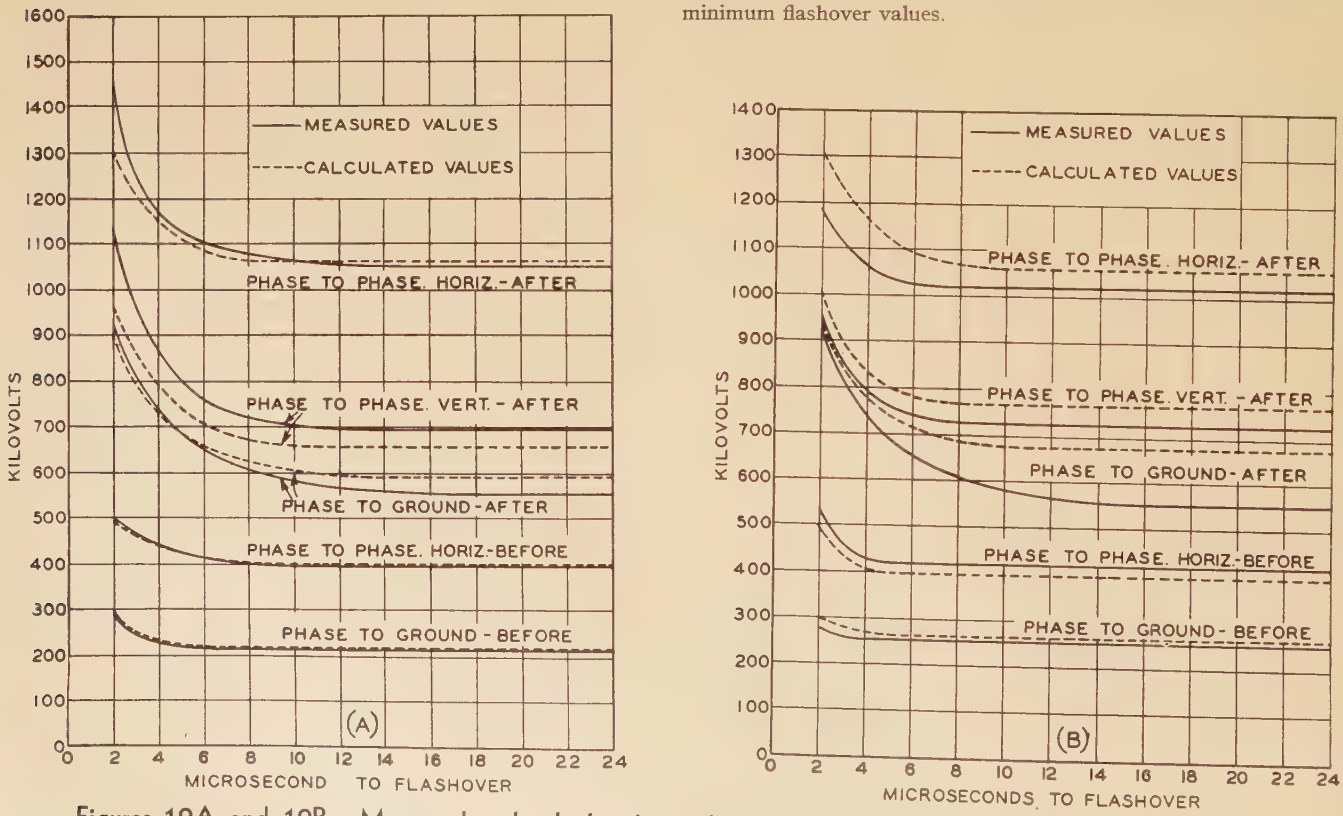
3. The flashover of wood insulating members is affected by the cross-sectional area of the wood, being in general lower the larger the wood section. The factors producing this result are not well understood and the subject should be further investigated.

4. The type of wood commonly used, for example, fir or pine, as used in crossarms, influences the flashover characteristics, fir having slightly higher flashover voltages than pine.

The volt-time characteristics also are different for the two woods, the characteristic for pine being steeper at short-time lags than for fir.

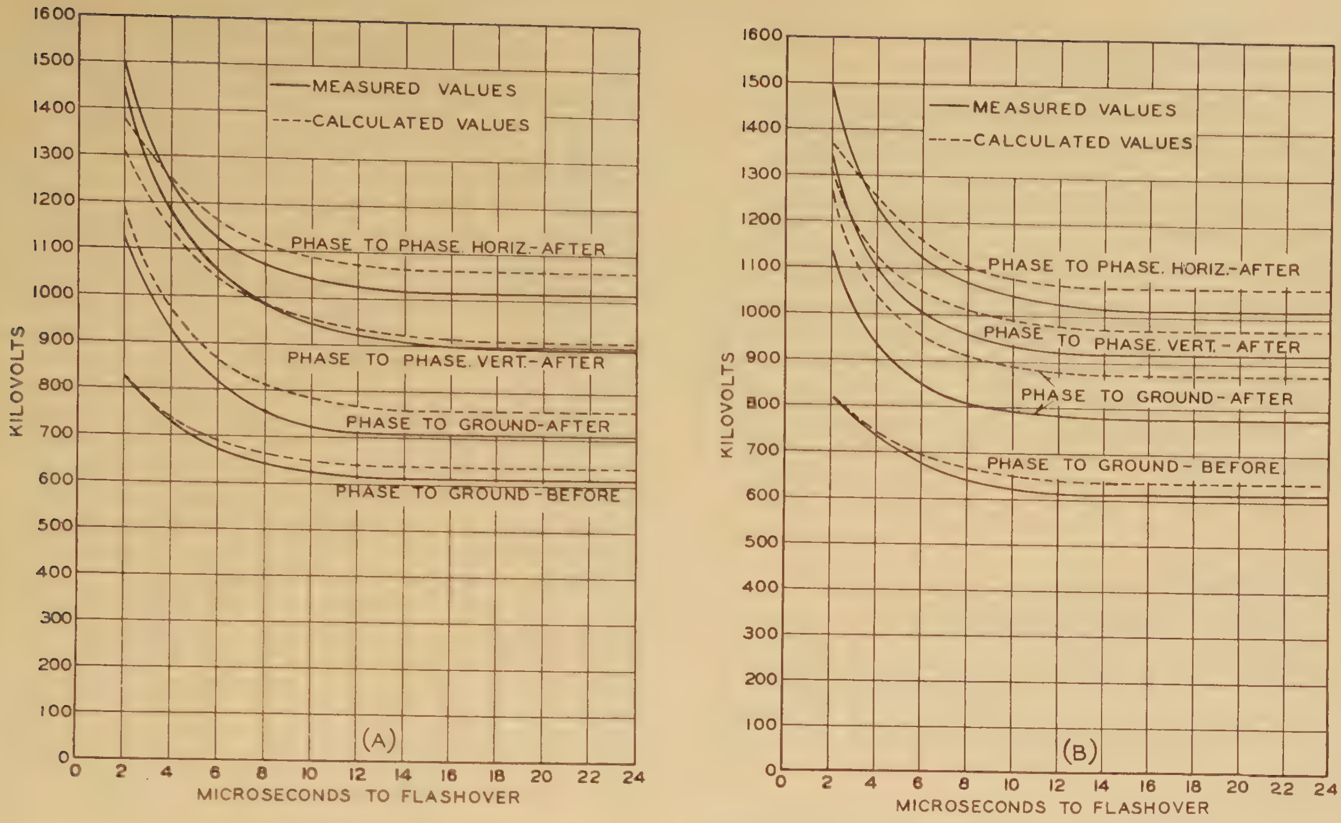
When used in combination with porcelain insulators, however, these different characteristics do not appear to be important.

5. The impulse flashover of cedar or aged pine wood poles appears to be very much the same and independent of treatment in lengths up to six feet. For greater lengths, a slight difference is indicated but of relative unimportance in selecting wood-pole material. New creosoted pine poles have considerably less impulse strength at minimum flashover values.



Figures 19A and 19B. Measured and calculated impulse strength of 33-kv wood structures of figure 15

A—Positive polarity *B*—Negative polarity



Figures 20A and 20B. Measured and calculated impulse strength of 66-kv wood structures of figure 16

A—Positive polarity
B—Negative polarity

6. The few tests made on wood under wet conditions indicate that its insulation strength is considerably decreased by the presence of moisture and rain. The preliminary work carried out indicates a reduction in impulse insulation of some 50 per cent under rain conditions. This is another point that needs further investigation.

7. The impulse insulation of wood in structures alone and in combination with porcelain can be calculated with a considerable degree of certainty. It is believed that the data presented here together with reduction factors obtained from tests on actual structures will be helpful in facilitating such calculations in the design of well-balanced wood transmission structures.

8. The data presented above, in the form of groups of curves giving the impulse characteristics of wood under various conditions, greatly amplifies our previous knowledge of the impulse insulating properties of wood, and should be useful in designing wood transmission structures to obtain greater benefit of the wood in supplying impulse insulation to the line. This is particularly important in the medium-voltage transmission lines where structures are inherently of wood, and until recent years, the insulation value of the wood has not been generally appreciated or made use of.

Considerable work still remains to be done in investigating further the impulse insulation strength of wood under various types of treatment, moisture content, and particularly under wet conditions simulating natural rain.

VII. Acknowledgments

The authors received material assistance in these studies from their associates and are particularly desirous of acknowledging the help received from Messrs. I. W. Gross of the American Gas and Electric Company, and C. J. Miller, Jr., of the Ohio Brass Company, in planning the tests and in analyzing the results. Most of the wood materials studied were furnished by The Ohio Power Company.

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Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 12 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the AIEE Pacific Coast convention, Spokane, Wash., August 31–September 3, 1937; and at the AIEE Middle Eastern District meeting, Akron, Ohio, October 13–15, 1937. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Distortion of Traveling Waves by Corona

Discussion and authors' closure of a paper by H. H. Skilling and P. de K. Dykes published in the July 1937 issue, pages 850–7, and presented for oral discussion at the power transmission and distribution session of the AIEE Pacific Coast convention, Spokane, Wash., September 1, 1937.

L. V. Bewley (General Electric Company, Pittsfield, Mass.): Skilling and Dykes have made a contribution of fundamental importance toward the solution of wave distortion due to corona. In 1931 Skilling developed a formula for the attenuation of the wave, assuming the losses to vary as the excess voltage above the critical corona voltage, but no provision was made in his formula for the associated distortion. In the present paper he has succeeded in formulating an equation for the distortion which occurs on the front of the wave, and which appears to give surprisingly good agreement with the oscillographic record.

I wish to point out, however, that his equation does not take cognizance of the presence of mutually coupled parallel wires and is, in fact, based purely on a single conductor wave. Consequently, the authors' statement under "Other Theories" to the effect that there would be no sharp distinction between their analysis and multivelocity theory is hardly tentable. In the *Conclusions* of my paper "Attenuation and Distortion of Waves," ELECTRICAL ENGINEERING 1933, attenuation and distortion are attributed to three principal causes: (1) multivelocity components, (2) a slippage effect at high voltage levels caused by a reduction in velocity of propagation corresponding to the larger diameters of corona envelope (Boehne's hypothesis), and (3) energy losses. The distortion described by Skilling and Dykes is that due to (2) and (3), and *not* to (1). Three conditions must exist before multivelocity waves can develop: (*a*) There must be a mutually coupled *multiconductor* system, (*b*) the applied waves on this system must be unsymmetrical (for example, the main wave impressed on only one of the conductors), and (*c*) the geometric factors determining the electrostatic field must be *different* than those determining the electromagnetic field, which is possible with a resistive earth or corona. It is therefore manifestly impossible for multivelocity components to be called into existence if only one conductor is present, or if equal waves are simultaneously impressed on all conductors of a system; and yet the Skilling and Dykes distortion is active under both these conditions. I think, therefore, that the crucial test of their formula is to those situations where multivelocities do not exist to mask the results, and thus hinder the segregation of this particular effect.

Contrary to the view expressed by the authors I do not believe that multivelocity components are comparatively negligible at high corona voltages. As shown in my paper referred to, corona calls into existence components of an essentially different character than those due to a resistive ground. This is startlingly revealed by the shape of the waves induced on adjacent conductors. In the case of corona in the presence of a resistive ground the fast and slow components of the induced wave are of the *same* polarity; whereas without corona they are of *opposite* polarity. This vital difference shows up on the oscillograms as a step in the case of corona and a loop in the case of ground resistance. It is quite interesting to observe in field tests a transition from one condition to the other as the voltage of the surge attenuates to lower values and the resistive ground effect begins to dominate. A further piece of evidence lies in the observed fact that in the presence of ground wires the attenuation is initially more but finally less than without ground wires.

It will be seen that the authors secure a much better agreement with tests on their single-conductor line than with the published oscillograms of other investigators who used multiconductor lines. This is because the waves have been retarded more by the separation of multivelocity components. Referring to figure 1 of the Brune and Eaton paper "Experimental Studies in the Propagation of Lightning Surges in Transmission Lines," waves *C*, *D*, and *N* were impressed on all three conductors, and it is clear that they differ materially from the others which were impressed on only one conductor of the system (and therefore developed multivelocity components). I suggest that Skilling and Dykes adjust their equation to waves *C*, *D*, and *N* of the Brune and Eaton paper, since these waves are not further distorted by multivelocity components. In this way the effect which they are studying is more accurately segregated. While I do not hold that the multivelocity components are the chief culprits in the attenuation and distortion accompanying corona (see fourth paragraph under the *Conclusions* of my paper referred to above), yet I feel that they are important enough to mess things up when a worthwhile attempt is being made to segregate the corona *energy loss* factor. There are so many factors responsible for attenuation and distortion (corona, resistive grounds, skin effect, leakage conductance, series resistance) that an investigation of any one of them should endeavor to isolate that one alone as nearly as possible.

Concerning the filling in of the tail of a wave, the authors have repeated the explanation given by Brune and Eaton. They seem inclined to ignore it for "practical cases" which is questionable advice. The wave tail is important in station protection problems, because when the wave impinges on the station capacitance the resultant voltage is very much dependent on the length of the wave, and will be greater the more the wave is filled in. In order to estimate the amount of this filling in I have, on occasion, gone to the other extreme and assumed that all of the space charge returns to the wave as its tail decreases. Thus in an article "Protection of Stations Against Lightning" by Bewley and Rudge, *G. E. Review*, August 1937, a chart is given based on the assumption that the surge attenuates in accordance with the Foust and Menger formula, and that the charge of the wave remains constant. Actually, of course, a large amount of the space charge never returns to the conductor until after the passage of the bulk of the wave (particularly in the case of positive surges), but the assumption errs on the safe side in calculating station voltages.

H. H. Skilling: The authors find themselves in almost complete agreement with the excellent discussion by Mr. Bewley, and wish to offer a reply to the question that he has raised. This regards the relative importance of the effect of "multivelocity components" of a traveling wave and the effect of distortion due to corona, when the crest voltage of the wave is substantially greater than the voltage necessary to produce corona on the line.

The question may be stated as follows: *Is the distortion of a traveling wave due to geometric factors, such as ground, ground wires, and near-by parallel conductors (as considered by Mr. Bewley in the theory of multi-velocity components) negligible when compared to the distortion of the wave due to corona loss, when the crest voltage of the wave is much greater than the corona-forming voltage of the line?*

It is certainly true that this question is not answered by the authors in their paper.

Mr. Bewley offers the following test: "I suggest that Skilling and

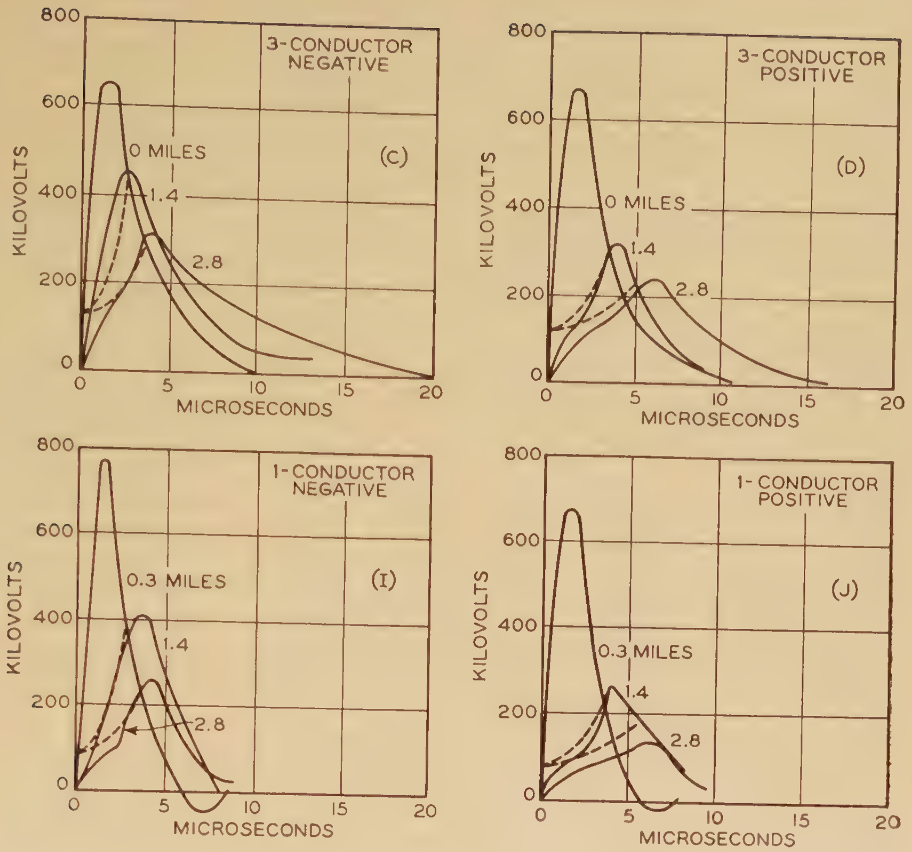


Figure 1. Computed waves compared with oscillograms by Brune and Eaton, waves C and D traveling on one of three conductors and waves I and J on all three

Dash lines computed

Dykes adjust their equations to waves *C*, *D*, and *N* of the Brune and Eaton paper, since these waves are not further distorted by multivelocity components." (Waves *C*, *D*, and *N* were impressed on all three conductors of the experimental transmission line simultaneously, and therefore would not develop multivelocity components.)

In carrying out Mr. Bewley's proposal, the authors went a step farther and compared computed values of waves with every one of the oscillograms reproduced by Brune and Eaton, if comparison was possible and appropriate. Brune and Eaton have sets of oscillograms for the following applied waves: their figures 1 and 2 show waves *A*, *B*, *C*, *D*, *I*, *J*, *K*, *L*, *M*, *N*; and their figure 8 shows a negative wave and a positive wave. Waves *K*, *L*, *M*, and *N* from figure 1 must be eliminated from this discussion because they are at all times below the corona-forming voltage of the line. The positive wave from figure 8 gives no opportunity for useful comparison because only one oscillogram of that wave is given with crest above the corona-forming voltage. There remain, then, waves *A*, *B*, *C*, *D*, *I*, and *J* of figure 1, and the negative wave of figure 8, for comparison with computed results. Of these, waves *C* and *D* were applied to all three conductors of the transmission line simultaneously, while *A*, *B*, *I*, and *J* and the negative wave of figure 8 were applied to only one of the three conductors, the other two conductors being present but not connected to the surge generator.

For comparison, curves from Brune and Eaton's paper are reproduced. Waves *A* and *B* from figures 1 and 2 of the paper by Brune and Eaton appear in figures 8*a* and 8*b*, respectively, of the paper by Skilling and Dykes (page 855). The other waves appear in figures 1 and 2 of the present discussion.

Distortion of all of these waves was computed with the following constants: $n^+ = 2^1/_4$, $n^- = 4$. No distinction was made between the case of waves on one conductor and the case of waves on three conductors. Of course, the corona-forming voltage and the capacitance were different in the two cases, and this was duly taken into account in the computation, but the factor n was unchanged. It will be remembered that the factor n is not merely an adjustable, empirical factor, as explained in the paper (pages 850 and 854). It is understood, however, that there is nothing in the authors' computations that takes into account the effect of near-by conductors on which no surge was applied. Consequently, if the distortion due to "multivelocity components" is a fairly large fraction of the distortion due to corona there should be decidedly better agreement between the computed results and the observed results when the surge was applied to all three conductors in parallel and there were no "multivelocity components."

Whether or not this is the case is purely a matter of judgment. Does it appear that there is better agreement between observed and computed results for waves *C* and *D* in figure 1 of this discussion than there is for waves *I* and *J* of figure 1, or for the wave of figure 2, or the waves of figure 8 of the paper? If the agreement seems about equally satisfactory in all cases (as it does to the authors) then it may be concluded that the distortion due to "multivelocity components" is, in these cases, very small compared to distortion due to simple corona loss, and that the formula (equation 14 of the paper) is reasonably correct despite the presence of near-by conductors.

One interesting detail of figure 2 of this discussion lies in the fact that Brune and Eaton give the form of the wave after it has traveled 2.8 miles, without giving the initial wave form. This figure, then, illustrates the statement in the paper that distortion can be predicted with *any* known form as data—it is not necessary to know the *initial* form. In fact, the initial form can be computed from the form of the wave at a distance of 2.8 miles along the line; this was done, and the result is shown in figure 2. Whether or not the computed initial wave is correct is not known, but it is quite consistent with other initial waves shown by Brune and Eaton. It must be noted, however, that the shape of the initial wave cannot be determined for voltages above the crest of the observed wave.

There is one point of interpretation on which the authors cannot agree with Mr. Bewley. He says, "It will be seen that the authors secure a much better agreement with tests on their single-conductor line than with the published oscillograms of other investigators who used multiconductor lines." The authors must confess that more trouble was encountered in fitting the distortion equation to their own results than to the published oscillograms of others. This is reflected in table I on page 856. Also it is felt that the poorest agreement appears in figure 3, page 852, where comparison is made to experimental results by Dykes; and the best in figure 9 of the paper

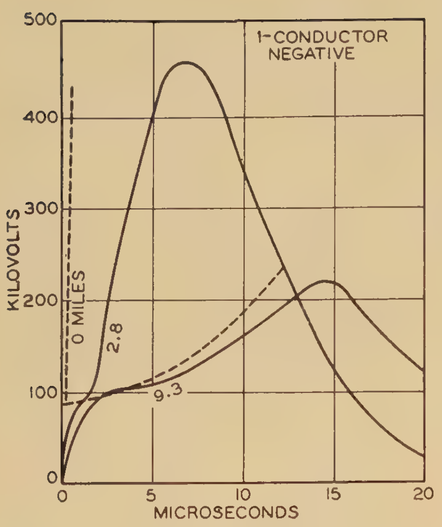


Figure 2. Negative wave traveling on one of three conductors; wave at source and at 9.3 miles computed from observed wave at 2.8 miles. Oscillograms from figure 8 of paper by Brune and Eaton

Dash lines computed

and figure 2 of the discussion, with waves of Conwell and Fortescue, and Brune and Eaton, respectively.

Finally, the use of a quadratic law of corona loss at power frequency must be explained. It is recognized by the authors that no relation so simple as a quadratic law is adequate to account for corona loss, and that this is particularly true for values of voltage in the neighborhood of the "corona-forming voltage." There were three reasons for using a quadratic law in this paper: first, it is a good analytic expression of the experimental loss curve shown in figure 4 of the paper, particularly at voltages above 75 kv; second, it is simple enough to be handled in the solution of the differential equation, equation 11; third, it is generally known (whether or not it is generally accepted) and it can readily be applied to a wide variety of conditions.

Several other expressions for corona loss were tried in the course of the study that led to this paper. At one time it was assumed that the loss was proportional to the first power of voltage above the corona-forming voltage; this described a traveling wave which was reduced at the crest but which maintained a constant slope of front—a result that is manifestly incorrect. Another attempt was based on loss proportional to the 1.6 power of the total voltage: this gave results that were good for high voltages, for it is a good approximation of the corona loss at high voltages, but it did not show a break in the front of the wave at the corona-forming voltage.

If it is possible experimentally to determine the actual corona loss on a line under investigation, that may be done. A true analytical expression can then be fitted to the loss curve, and equation 11 may be rewritten and solved for that special case.

Transmission Lines at Very High Radio Frequencies

Discussion and author's closure of a paper by Lester E. Reukema published in the August 1937 issue, pages 1002–11, and presented for oral discussion at the communication session of the AIEE Pacific Coast convention, Spokane, Wash., September 2, 1937.

S. A. Schelkunoff (Bell Telephone Laboratories, Inc., New York, N. Y.): In the course of his paper and in the concluding paragraph Professor Reukema states that a shorting disk used to short a coaxial line does not radiate. He further says: "Since such a disk does not radiate power itself, it cannot prevent the radiation of power through it from the current in the line." Thus, according to Professor Reukema, *power is radiated* from a coaxial pair shorted at both ends with conducting disks and energized by a generator somewhere in series with the inner conductor. But in reality, if the outer conductor and the shorting disks are perfect conductors, *there can be no radiation* since the electric field tangential to this outer surface, and consequently the Poynting flux, vanishes. In any practical case, the outer conductor and the shorting disks are not perfect and a small amount of power escapes through them. At high frequencies, however, this power is exceedingly small because of the skin effect. In any case, this is not the radiation with which Professor Reukema is concerned since his calculations of radiation are based upon a tacit assumption that the conductors are perfect. The most convincing argument consists, perhaps, of actual calculations similar to those contained in my paper on "Some Equivalence Theorems of Electromagnetics and Their Application to Radiation Problems," published in the *Bell System Technical Journal*, January 1936. These calculations show that the radiation resistance of the shorting disk is $\left(\frac{2\pi S}{\lambda^2}\right)^2$ ohms, where S is the area of the disk ($S = \pi b^2 - \pi a^2$) and λ is the wave length. It is assumed, of course, that the radii a and b are small compared with the wave length.

In the section on "Radiation Resistance of Parallel-Wire Lines" the total radiation resistance of a circuit comprised of two parts is apparently obtained by Professor Reukema by adding the radiation resistances of the individual parts without taking into account the *mutual* radiation resistances. That this procedure is dangerous is amply shown by the following example. It is well known that the radiation resistance of a short wire of length l is $80\pi^2\left(\frac{l}{\lambda}\right)^2$. Applying Reukema's procedure to two short wires, placed end-to-end to make a wire of length $2l$ we obtain $2 \times 80\pi^2\left(\frac{l}{\lambda}\right)^2$ ohms for the radiation resistance of the longer wire, instead of the correct value $80\pi^2\left(\frac{2l}{\lambda}\right)^2$ ohms. Since the latter figure is twice the former, it is evident that the mutual terms are equal to the radiation self-resistances. Another example is furnished by a coaxial transmission line one-half wave length long, open at both ends, and energized from the center. The radiation resistance of either conductor is about 73 ohms, barring small correction terms depending upon the radius (the radius is supposed to be small compared with λ). If the mutual radiation resistances are disregarded, the radiation resistance of the coaxial pair becomes 146 ohms. In reality the mutual radiation resistance is such that the principal terms in the total radiation resistance cancel, leaving only the small correction terms which depend upon the radii. In general, the complete expression for the flow of energy per unit area is

$$E \times H = (E_1 + E_2) \times (H_1 + H_2) = E_1 \times H_1 + E_1 \times H_2 + E_2 \times H_1 + E_2 \times H_2$$

where E_1, H_1 and E_2, H_2 are the fields produced by the currents in the separate parts of the complete radiating circuit. Evidently the middle terms are the mutual energy terms; they may be either positive or negative. In very special cases, of course, the middle terms may vanish.

C. W. Hansell and P. S. Carter (RCA Communications, Inc., Rocky Point, N. Y.): The section of this paper which treats the radiation from concentric lines is of particular interest to us since we have had considerable practical experience with numerous transmitters using concentric lines for frequency stability. We disagree with the author's conclusions concerning radiation from concentric lines. Contrary to the author's conclusion there would be no radiation from a concentric line of perfectly conducting material closed at both ends. In a practical arrangement wherein the transmitter is entirely shielded with copper of ordinary thickness and this shield is made continuous with the outside conductor of a concentric line the radiation is negligible. Both practice and correct theoretical analysis substantiate the truth of these statements.

Reukema cites as an example a quarter-wave line for 60,000,000 cycles per second for which we gave a Q of 20,000 whereas he has calculated the Q to be only 3,420. He states that radiation is 5.6 times the other power losses or 85 per cent of the total power input to the line. According to this statement resonant lines should radiate almost as much of the total input power as dipole antennas

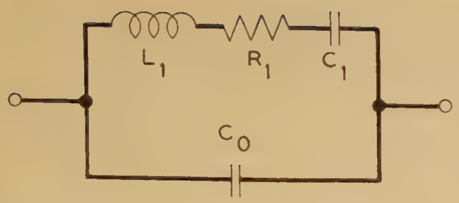


Figure 1

and there should be intense electromagnetic fields in the space surrounding them just as there would be in the space around an antenna. As a matter of fact completely shielded transmitters with resonant-line frequency control, such as those in commercial service on the radio relaying circuits between New York and Philadelphia, operated by RCA Communications, Inc., have so little radiation that a sensitive receiver is required to detect their radiation in the transmitter room. Even this radiation has been shown, by probe tests, to be leaking out over the power leads which are not quite perfectly filtered.

We have some resonant line installations in which power inputs to the resonant lines are on the order of kilowatts but still the electric fields surrounding them are negligible. If we actually radiated 85 per cent of the line input power, as Reukema says we do, we know from experience with unshielded circuits and indoor antennas that the transmitter room would be filled with intense electromagnetic energy by means of which lamps could be lighted without wires and operators would be subjected to great discomfort from high-frequency heating and artificial fever.

As a matter of fact Reukema's conclusions are contrary to common experience with high-frequency shielding. Most radio engineers are so well aware of the effectiveness of shielding that they take it for granted a water-tight metal enclosure completely surrounding any kind of high-frequency electrical circuit, regardless of shape or dimensions, will make the radiation negligible.

To connect up experience with theory let us consider a concentric line made up of perfect conductors which is closed at both ends and includes within it a radio transmitter. The energy generated by the transmitter is stored in the electromagnetic fields existing in the space between the conductors because a perfect conductor can sustain no electric field. In order for energy to be radiated from such a line an electromagnetic wave must penetrate the conductor. However, an electromagnetic wave cannot exist without storage of energy in the electric field and we have just stated that a perfect conductor can sustain no electric field. It therefore follows that passage of electromagnetic waves through the outer conductor and radiation from such a line could take place only by violating the fundamental laws of electromagnetic theory.

The author shows no derivation of the formulas given but, to one who is familiar with such problems, it is apparent that perfect conductors were assumed. Since these equations show very definite and comparatively large amounts of radiation the question naturally arises as to wherein lies the error. The well-known transmission line equations are only approximations which, while sufficient for most engineering purposes, are inadequate for treating the radiation from a concentric line. It is evident that the current distributions assumed in deriving the formulas given were taken from the common transmission line equations. A fundamental analysis of a concentric line indicates that such current distributions can exist only along the central portion of a line many wave lengths long, yet these current distributions have been assumed to hold for lines even shorter than a quarter wave length. Although an exact solution of the wave equation for a finite concentric line having closed ends is exceedingly difficult, if not mathematically impossible, we can state that no distribution of currents within such a system can exist which will produce other than zero electric or magnetic field strengths at *all* positions lying outside the conductors.

An electromagnetic wave will penetrate an imperfect conductor such as copper. However, at the very high radio frequencies under consideration here the attenuation of such a wave is so extremely high that the radiation passing through copper of any thickness ordinarily used would be of an infinitesimal amount in comparison with the quantities under consideration in the formulas of this paper.

W. P. Mason (Bell Telephone Laboratories, Inc., New York, N. Y.): In his interesting paper on radiation from transmission lines Professor Reukema has made some valuable calculations on the effect of radiation on the Q of balanced and concentric lines which should be a contribution to their use as circuit elements. He appears to feel, however, that the use of crystals in the ultrahigh-frequency region is not feasible, for he states that "The Q of a crystal (defined as the ratio of its inertial reactance to its frictional resistance) is inversely proportional to the frequency and assumes such a low value at the ultrahigh frequencies as to be practically worthless for frequency stabilization." He mentions values of the Q of a crystal as 170 at 30 megacycles and 17 at 300 megacycles. Fortunately these statements do not agree with our experience.

Since no published values of the Q's of crystals over wide frequency ranges are available it was thought worth while to measure a number of crystals covering a wide frequency range. Accordingly a number of AT and BT crystals whose fundamental frequencies varied from 800 kilocycles to 20 megacycles were measured. The Q of a crystal is defined with respect to the equivalent circuit of the crystal shown on figure 1. Here the static capacity of the crystal is designated by C_0, while the effect of the motional impedance of the crystal is represented by the series resonant circuit L_1, C_1, and R_1. The Q of the crystal is defined as the ratio $(2\pi f_R L_1)/R_1$ where f_R is the resonant frequency.

At the lower frequencies the method used to measure the Q was the one described in a former paper ("Electric Wave Filters Employing Crystal as Elements," *Bell System Technical Journal*, July 1934, page 431) and shown on figure 2. It consists of measuring the resonant frequency f_R, the antiresonant frequency f_A, the resistance at resonance R, and the static capacitance of the crystal C_0. From these the Q of the crystal can be calculated from the formula

$$Q = \frac{f_R^2/(f_A^2 - f_R^2)}{2\pi f_R C_0 R} \doteq \frac{1}{4\pi R C_0 \Delta} \text{ where } \Delta = f_A - f_R \tag{1}$$

At higher frequencies the measurement of resistance becomes less reliable. At these frequencies, however, the reading of vacuum-tube voltmeters is satisfactory, so the circuit of figure 2 was modified to that of figure 3, and the resonant and antiresonant frequencies were measured as well as the voltages across the low terminal resistance at resonance and antiresonance. It is readily shown that the Q of the crystal will be given by the formula

$$Q = \frac{f_R}{2\Delta}\sqrt{\frac{V_R}{V_A}} \text{ where } \Delta = f_A - f_R \tag{2}$$

and V_R and V_A are the voltages across the terminating resistance at the resonant and antiresonant frequencies, respectively. A third method tried was to measure the voltage across the terminating resistance at antiresonance and a few cycles from antiresonance. For this case the Q of the crystal is given by the formula

$$Q = \frac{f_A}{2\Delta}\left[\left(\frac{V_C}{V_A}\right)^2 - 1\right] \tag{3}$$

where Δ is the difference in frequency between the antiresonance and the frequency for which the voltage V_c is measured. All three of these methods were compared on several crystals and checked within a few per cent.

The measurement of Q for the fundamental frequency for nine

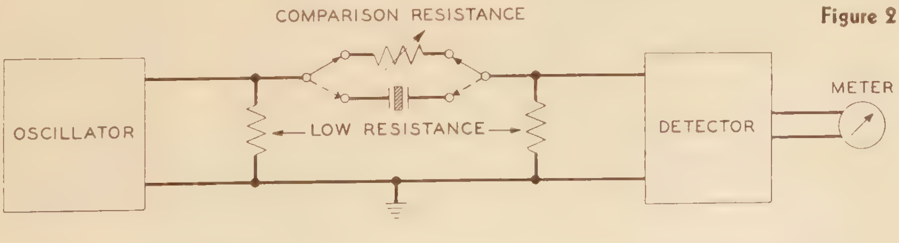


Figure 2

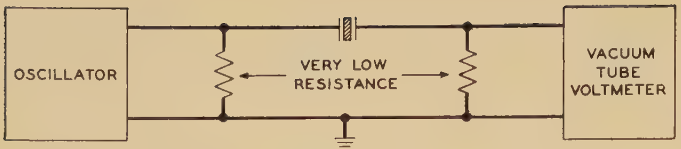


Figure 3

AT and *BT* crystals is shown on figure 4. These crystals were all measured in an air-gap holder in the open air. As can be seen from the figure, there is no significant trend with frequency. The individual difference between crystals is so large that it masks any frequency trend. This difference in Q between shear vibrating crystals is thought to be mainly due to differences in the surface caused by grinding. If the surface layer is taken off by etching or polishing, the Q in general is considerably higher. The shape or size of the crystal does not appear to affect the Q in any significant manner. In any case the Q of crystals at 20 megacycles—which is about as high in frequency as it is feasible to measure the characteristics of crystals with electric oscillators on account of the instability of the electric oscillator— is in the order of 30,000 to 70,000 which is much higher than the figure of 250 which would be obtained using Reukema's data.

Another method for attaining high frequencies with crystals whose thickness can be obtained commercially is to use a mechanical harmonic of a shear vibrating crystal. The electromechanical coupling of such a crystal decreases about inversely as the order of the harmonic, and the ratio of capacities inversely as the square of the harmonic. Nevertheless by using special oscillator circuits it is possible to drive such crystals and have them control the frequency of oscillators. Hence it is of some interest to find how the Q for the successive harmonics varies. For this purpose three crystals were measured having respectively fundamentals of one megacycle, two megacycles, and eight megacycles. The first 15 harmonics of the one-megacycle crystal were measured and the result is shown on curve 1 of figure 5. As can be seen the Q increased with frequency from 93,000 for the fundamental to nearly 400,000 for the fifteenth harmonic. This is what would be expected if most of the dissipation is located in the surface layers, for the harmonic crystal as shown on figure 6 is equivalent to a number of fundamental crystals in combination. If most of the dissipation is located on the two outside layers it is obvious that the effect will be inversely proportional to the number of dividing surfaces or loops and will be considerably smaller for a harmonic crystal than for a fundamental crystal. Crystals 2 and 3 also show its effect of increase in Q with harmonic order but they do not rise to as high limiting values as the first crystal. This is probably due to their lower initial value since the dissipation introduced by the outer faces is higher for them than for the first crystal.

It is concluded from these measurements that after eliminating known dissipative losses in crystals, that there is no evidence of a dependence of Q of a crystal upon frequency.

Professor Reukema, as a result of his opinion on the Q of crystals, seems to feel that crystals will not give frequency stability in the ultrahigh-frequency range as good as can be secured with resonant lines. This again is not in agreement with our experience. Evidence for the use of crystals in stabilizing high-frequency oscillator circuits is furnished by work recently done at Bell Laboratories on a direct crystal-controlled oscillator working at 120 megacycles. This oscillator, which it is hoped to describe in a forthcoming paper, works on the fifteenth harmonic of an eight-megacycle crystal. With plate voltage changes, the frequency of this oscillator does not change more than 0.05 cycles per megacycle per volt change which does not differ much from the voltage stability of ordinary crystal oscillators at low frequencies. Hence we can conclude that crystals in harmonic vibration can be used to control the frequency of ultrashort-wave oscillators and give good stability.

Lester E. Reukema: If my statement regarding the Q of crystals at very high frequencies is responsible for the initiation of the experimental work on the subject reported in Mr. Mason's discussion of my paper, it is fortunate that I made the statement even though it seems to be erroneous. For until this discussion of Mr Mason's appeared, it seemed to be universally accepted by all workers in the field of crystals, at least so far as the published literature is concerned, that the Q of a crystal was inversely proportional to frequency. As proof of this universal acceptance refer to any textbook which even mentions the subject or to the published literature dealing with the equivalent electrical circuit of the crystal. For instance, in Hund's "Phenomena in High-Frequency Systems," combine equation 51, page 311, namely

$$\omega_0 = \frac{540{,}000\,\pi}{b} \quad \text{or} \quad f_0 = \frac{270{,}000}{b}$$

where b is dimension of the crystal in the direction of vibration and f_0 is the resonant frequency of the crystal, with equation 57, page 313, namely

$$\Delta = \frac{R}{2f_0L} = \frac{0.00202}{b}$$

where Δ is the logarithmic decrement of the crystal, and R and L are the equivalent resistance and inductance of the crystal. This gives

$$Q = \frac{2\pi f_0 L}{R} = \frac{\pi}{\Delta} = \frac{\pi b}{0.00202} = \frac{270{,}000\,\pi}{0.00202 f_0} = \frac{420{,}000{,}000}{f_0}$$

According to this formula, at $f_0 = 30{,}000{,}000$ cycles, $Q = 14$, which is even lower than the value of 170 which I gave. However the decrement depends on the degree of polish of the crystal faces, the way the crystal is held in the holder, and on the air friction, and the constant involved in Hund's equation 57 may readily be decreased to considerably less than the value he gives. In the example given in my paper, I decreased the value of the constant to about one twelfth Hund's value, on the basis of values of Q given in the published literature, thus raising the value of $Q = 14$, as computed from Hund's formula, to my value of 170 at 30,000,000 cycles. The important part of Hund's formula is that it gives Q as inversely proportional to frequency.

I might also quote from Terman's "Radio Engineering," 1932 edition, top of page 265, "...and finally that the effective Q of the

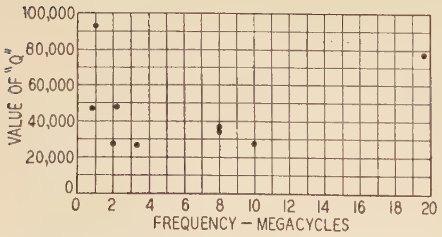


Figure 4. Measurement of Q of AT and BT crystals as a function of frequency

All crystals measured on fundamental mode of vibration

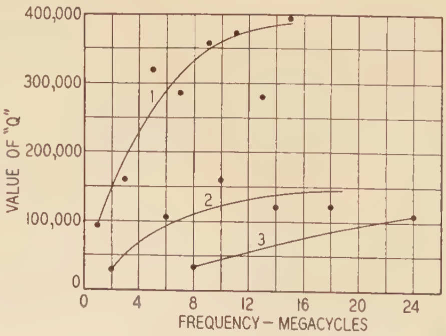


Figure 5. Measurement of the Q of the fundamental and harmonics of three crystals

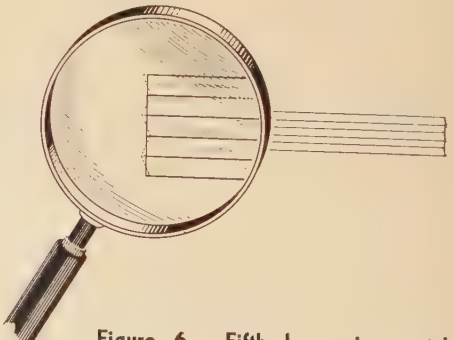


Figure 6. Fifth harmonic crystals showing planes of maximum motion

crystal vibrator varies *inversely* with frequency...." Terman's 1937 edition contains the same statement. This conclusion is reached also in computing Q from the equations for the equivalent R, L, and C of the crystal, as derived by K. S. Van Dyke in IRE *proceedings*, volume 16, 1928, page 743, and as accepted and repeated innumerably since then by the other workers in the field. If Mr. Mason's experimental results are correct, and I have no reason to believe they are not, then universally accepted mathematical analysis of the equivalent electric circuit of the crystal is sadly in need of revision.

Let us consider now the discussion of C. W. Hansell and P. S. Carter. They claim that according to my calculations resonant concentric lines should radiate almost as much of the total input power as dipole antennas. Actually my formulas show that the radiation resistance of their quarter-wave shorted concentric line at 60 megacycles is only 0.01455 ohms, as compared with 73.14 ohms for a dipole antenna. In other words, the concentric line, instead of radiating almost as much energy as a dipole, would radiate only one five-thousandth as much energy as a dipole. For a correctly designed short half-wave concentric line, the radiation resistance is only 1/33,200 that of a dipole. The reason the small amount of energy radiated from a concentric line, used to control the frequency of an oscillator, is not negligible, is that the other losses in the line *are so much smaller*. Of course I did not make the statement that 85 per cent of the power *input* to a concentric line is radiated. It is well known that the loss in concentric lines used to feed power to transmitting antennas is almost negligible, and no one would say that 85 per cent of the input power to such a line was radiated by the line. What I did state was that the loss due to radiation in a particular line used by Carter and Hansell to control the frequency of an ultrashort-wave oscillator, was 5.6 times as great *as the other losses in that line*, and the sum of all the losses is so small that the talk of generating artificial fever in the operators by means of the radiated energy is not valid.

They also state several times that "a perfect conductor can sustain no electric field." The outer surface of a concentric line is a perfect conductor only to the same extent that the surface of a radiating antenna of the same outer diameter is a perfect conductor. Yet everyone knows that voltages of many thousands of volts are set up between the ends of such radiating antennas, as evidenced by the necessity for insulators at the ends. What they should say is that a radiated field, striking such a perfect conductor, cannot set up an electric voltage across it because the resultant movement of electrons in the perfect conductor is such as to exactly neutralize the voltage induced by the field, just as the voltage induced in the secondary winding of a shorted transformer is neutralized by the movement of electrons through the winding itself, leaving zero voltage across the terminals. My computations of energy radiated do not presuppose that a field from *within the concentric line* penetrates the outer conductor, but rather that part of the current in the outer conductor flows on the outer surface, which allows it to radiate just as from any ordinary antenna.

To see that this is so, let us consider first a complete radiating system, entirely enclosed in a copper shield, the shield itself *forming no part of the enclosed circuit*. Any field striking such a shield from within induces in it a voltage which causes a current to flow on the *inner* surface of exactly the value to consume the induced voltage and no energy penetrates the shield (assuming perfect conductivity). Even for ordinary shields the energy which penetrates the shield is infinitesimally small. Since at every point of the shield the flow of electrons on the inner surface exactly neutralizes the voltage induced by the field the voltage difference between any two points on the inside of the shield is zero. Moreover, since no energy can penetrate the shield, the voltage between any two points on the outside of the shield is also zero, so of course no current flows on the outside. In other words, a shield *which forms no part of the enclosed circuit* is exceedingly effective in preventing the radiation of energy through it as amply proven by any number of accurate experimental measurements.

Consider now a concentric line, shorted at both ends and of such length as to be resonant, the length being assumed to extend from a circle halfway between inner and outer conductors on one shorting disk to the corresponding circle on the other shorting disk. Consider a source of high-frequency voltage to be impressed between inner and outer conductors of such frequency as to make the distance between inner and outer conductors an appreciable fraction of a quarter wave length. The field radiated from the inner conductor induces a voltage on the inner surface of the outer tube, causing a current to flow there lagging exactly 180 degrees behind the field which produced it and of such magnitude as to completely reflect the wave back into the inner space. But since the current induced in the outer tube by the field from the inner conductor lags 180° behind the field, it lags *more* than 180 degrees behind the current in the inner conductor, since it requires a finite time for the field to travel from inner conductor to outer tube.

However, the outer tube is acting as the return conductor for the inner tube, and therefore must carry a current *exactly* equal and opposite that carried by the inner tube, if there is to be no voltage set up between the ends of the concentric line. Since the current which flows on the inner surface of the outer tube, due to the field radiated from the inner conductor, is *not exactly equal and opposite* the current on the inner conductor, a slight voltage is set up across the ends of the concentric line, which causes a current to flow on the outer surface of the outer tube, equal to the vector difference between the currents already considered. Of course both radiated and inductive components of the field due to the current on the inner conductor must be considered, in computing the current which flows on the outer surface of the outer tube. When the spacing between inner and outer tubes is very small compared to a quarter wave length, as is the general case except at the ultrashort wave lengths, this outer current is practically infinitesimal. Even at the ultrashort waves, the outer current is so small compared to the current which flows on the inner surface of the tube, that the energy radiated is of the order of 0.01 of 1.0 per cent of that which would be radiated if all the current were on the outside. However, *small as it is, the energy radiated is by no means negligible, compared with the other losses in the concentric line.*

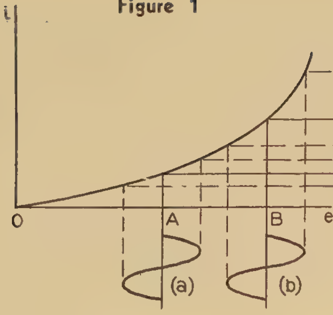
This point has been neglected both by Carter and Hansell and by Schelkunoff, which is the reason that the latter finds a finite radiation resistance from a perfectly conducting shorting disk, whereas my equations show this radiation resistance to be exactly zero. Mr. Schelkunoff's remarks concerning my direct addition of the radiation resistance of a shorted parallel-wire line to the radiation resistance of the shorting bar are perfectly correct. For high accuracy the *mutual* radiation resistance would have to be considered. However, the fact that the line and the shorting bar are perpendicular to each other makes the mutual radiation resistance quite small, compared with the total radiation resistance, and I neglected it because there seems no way to combine it with the other results *for all lengths of line* without making the equations unwieldy. In any case my conclusion that the shorted parallel-wire lines should be brought together at the far end gradually, thus eliminating the necessity for a shorting bar would be in no way changed.

A Review of Radio Interference Investigation

Discussion and authors' closure of a paper by F. E. Sanford and Willard Weise published in the October 1937 issue, pages 1248–52, and presented for oral discussion at the selected subjects session of the AIEE Middle Eastern District meeting, Akron, Ohio, October 13, 1937.

W. C. Osterbrock (University of Cincinnati, Cincinnati, Ohio): The location of sources of radio interference such as are described in this paper is in many cases quite difficult and this is largely due to the fact that faults capable of creating serious interference with radio reception may be entirely insignificant in their effects on the electric service. A good illustration of this possibility is reported in the editorial page of *Electronics*, September 1937, by R. L. Peterson. In this instance, the uncertain contact between turns of the armor on BX cable produced a variable impedance such as re-

Figure 1



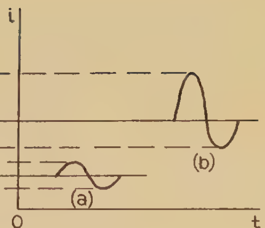


Figure 2

ferred to in the section on "External Cross-Modulation" of the paper, and this gave rise to the effect described, namely background tone from one or more interfering stations. It would seem that the location of such a fault might require, in addition to good measuring technique, a slight touch of genius.

The manner in which cross-modulation is produced by a nonlinear impedance may be considered qualitatively by reference to figure 1, which shows the current in such an impedance as a function of the voltage, and figure 2, which shows current as function of time for two different conditions.

In figure 1, (*a*) represents the desired signal voltage when the interfering signal has a value *OA*, and (*b*) represents the same voltage for an interfering voltage *OB*. The corresponding currents are shown at (*a*) and (*b*) of figure 2, and are seen to be quite different. In the course of modulation the interfering voltage varies from *OA* to *OB*, and the sensitivity of the system to the desired signal is caused to change correspondingly. As a result the modulation of the unwanted station is heard as a more or less distinct background.

The above analysis is not complete, as it ignores the rapid variation of interfering signal during the cycles (*a*) and (*b*). A more satisfactory procedure is to develop the current function into a Taylor's series, and if this is done, it turns out that the third-order term causes a current component to appear *having the same frequency as the desired signal*, but whose amplitude is a function of the interfering signal voltage. The receiver is of course tuned to this frequency in question, and responds as well to this particular component as to the original signal. Incidentally, the cross-modulation term is proportional to the *square* of the interfering signal voltage, and thus every increase in power of a local broadcast transmitter can be expected to produce a flood of new complaints.

As mentioned in the paper, the interference may be transmitted to the receiver by reradiation from the offending conductor, but it may also arrive there via the line cord. Whether it does or not will depend largely upon the effectiveness of the receiver grounding system.

The authors are to be commended for their thorough review of the situation, and their company for its enlightened policy in the investigation of complaints. Many cases have come to my attention of painstaking investigation by their radio squad, even though only a remote possibility existed that the trouble might be due to some fault in the lighting service.

J. J. Smith (General Electric Company, Schenectady, N. Y.): The authors deal with the problem of radio interference from the point of view of a utility whose territory is close to one of the broadcast centers. Under these conditions the radio set users would expect to get good reception. It is interesting to note in table I that 18 per cent of the complaints investigated were due to receiver trouble as compared with 11.5 per cent which were due to the company's distribution lines and equipment. The statement that the number of power cases is only about 25 per cent of what it was in the first years of the investigation work is encouraging. The trend toward greater co-operation between the power company investigations and the radio service men is also an indication that progress is being made.

The thing that is needed now is to carry out studies on a quantitative basis. The authors refer to the results that have been accomplished through inductive co-ordination of power and telephone systems. These results would not have been possible without the quantitative data obtained co-operatively through the joint Subcommittee on development and research of the EEI and Bell Telephone System. To obtain such data, wave-shape surveys have been made on a number of power systems in different parts of the country, coupling coefficients have been measured between typical power and telephone systems, data have been obtained on the characteristics of telephone circuits and apparatus, and many other studies have been made or are in progress.

A similar approach to the problem of radio interference which the paper suggests would involve the collection of data on signal strengths of broadcasting stations and noise levels in different localities, data on coupling between radio receivers and electric circuits in houses, data on characteristics of power apparatus, etc. Such a study is being carried on by the joint co-ordination committee on radio reception of EEI, NEMA, and RMA. The committee has recommended suitable instruments and methods, and issued a report entitled "Methods of Measuring Radio Noise" which is available through the headquarters of the EEI, NEMA, or RMA. This report gives specifications for the instrument recommended for measuring radio noise and the procedure to follow in the use of this instrument. Subcommittees have also been set up for collecting and correlating quantitative data and it would be of great assistance if those who are doing field work like the authors of the paper would obtain more data and report their results in the form suggested by this joint subcommittee.

P. L. Bellaschi (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): Radio noise from power sources presents problems of a complex character but fortunately in practice many of these can be approached and disposed of satisfactorily through relatively simple procedure, as Messrs. Sanford and Weise have indicated in their paper. The fundamental aspect of radio noise remains, on which considerable progress already has been made.

An important contribution to this progress has been made possible by the joint co-ordination committee on radio reception of EEI, NEMA and RMA, in specifying suitable and adequate methods of measuring radio noise. Mention should be made of EEI publication No. *C*-9 or the corresponding NEMA (No. 102) or RMA (No. 13) publications.

The above mentioned technique and methods of measuring radio noise have been applied for a number of years at the East Pittsburgh laboratory of the Westinghouse Electric & Manufacturing Company ("Measuring Radio Interference from High Voltage Apparatus," C. V. Aggers and W. E. Pakala, *The Electrical Journal*, December 1933). Another laboratory, fulfilling the EEI-NEMA-RMA recommendations has recently been installed at the Sharon plant of the same company. Comparison of measurements have been made between these two laboratories to correlate results. For example, when a simple electrode arrangement as a rod to plate was employed the characteristic curves of voltage versus microvolts for the two laboratories are found to come within a few per cent of each other. Even wider variations would be considered good agreement at the present status of the art.

Fundamental investigations always should present room for possible improvement and refinements both in the technique and the methods of measurement. Yet experience has well demonstrated that in the long run much is to be gained through orderly standardization of methods and technique. It is for these reasons that the general application of the methods recommended by EEI-NEMA-RMA hold out promise toward a rapid rationalization of the radio noise problems. As Messrs. Sanford and Weise have clearly stated the complete elimination of all radio interference appears uneconomical, the aim being chiefly to establish permissible levels for electrical apparatus which are reasonable and economically feasible.

F. R. Benedict (nonmember; Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Short-wave and broadcast program listeners are confronted at one time or another with radio interference which makes reception very unpleasant. Unfortunately, the general public has not been educated in the problems associated with interference and interference producing devices, but only know of it by the interference to their favorite program. Usually this interference is not under the control of the listener and his dissatisfaction is accompanied by a feeling of frustration, which is directed at the world in general. For the past seven years, a group of engineers have been working on the problem of interference and its relation to broadcast reception. This group has been studying the co-ordination of the newer uses of electricity with its older uses for power, light, heat, transportation, and communication, so that the growth of each of these will not be restricted by the requirements of the others. This program is being carried on by the joint committee on radio reception of the Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association. Preferred methods of measurement have been developed and appear in the NEMA publication No. 102. Consideration is also being given to factors in the design of machines and power systems which may affect radio reception. The characteristics of radio receiving sets and the relation of shielding, sensitivity and selectivity to the elimination of radio noise, is also being carefully studied.

The source of radio interference can be determined by the audio characteristics produced in the radio loud speaker. The different types of interference may be classified in two groups, (*a*) uncontrollable interference and (*b*) controllable interference. Under class (*a*) are found atmospherics, i.e., lightning, background static, solar interference, snow and sleet static, etc. Under class (*b*) are found commutating machines, transmission line equipment (such as bushings, pin insulators, transformers, etc.), diathermy machines, sign flashers, auto ignition, etc.

The first class of interference is termed uncontrollable because of the engineer's inability to deal with the source of the noise. It is present at all times, although the amount of trouble it will produce varies considerably with time, weather conditions, and from one locality to another. Radio engineers have done much to improve this condition in modern receivers by increasing selectivity, or in short designing for a high signal to noise ratio. Another aid in eliminating trouble from this class of interference is obtained through increasing the power of broadcast stations and making use of transmitting antennas, which will increase the field strength within the normal coverage area. If the signal strength at the receiving antenna can be increased, the ratio of the signal voltage to the noise voltage appearing on the input of the receiver will be increased and the amount of annoyance caused the listener will be eliminated.

The greatest help for the distant listener would be an ideal receiving antenna system and an increase in broadcast station power to bring up the field strength at the listener's antenna. The problem is not so easily solved. Broadcast stations cannot use unlimited power since allotment of transmitting frequency necessitates more than one station on the same frequency with the possibility of interstation interference. Advances are being made in the use of directional antennas and improvement in broadcast station coverage may be expected in the future.

The progress in elimination of atmospherics has been slow as the static interference seems to have transmitting characteristics over the whole broadcast and short wave spectrum. Various schemes of frequency and amplitude modulation have been advanced for reducing atmospheric disturbances in radio receivers, but these schemes are still in the experimental stages and promise only a partial solution to the problem of uncontrollable interference.

That interference classed as controllable or man-made, has become a serious problem. With electric service increasing daily, the need for some consideration of radio interference problems and their relation to the rapidly growing electrical industry, is very essential. At the present time there are a great many devices in use which produce objectionable interference in nearby radio sets when operated on the supply mains. In the next few years many more will be sold and, in themselves, add measurably to the present problems. In many metropolitan areas, where field strengths are low, the problem is already acute. The interference in such areas, is mainly caused by appliances or other electrical devices common to all electrified households. Vacuum sweepers, food mixers, universal motors, electric razors, electric fans, electric toys and many other devices may come under the category of interfering devices. Of these, those devices classed as commutating machines cause the most radio interference troubles.

It is well known that scientifically designed and properly installed filters may be applied in many cases for the reduction of radio interference from electrical appliances. It may be asked—"Why not apply filters to all household appliances which may produce interference and thereby alleviate all future trouble from such appliances?" In answering such a question satisfactorily, consideration must be given to many factors, which are closely allied with the whole interference problem.

The problem begins in the radio owners' homes and simply stated is "For an appliance with known radio noise output voltage connected to the supply lines of the home, how much noise voltage will be induced in the receiver antenna and ground system?" This can only be determined by experimentally finding the ratio of interference noise measured in the factory to that which may be induced in the antenna when in operation on the home supply lines.

Tests made in homes in the Pittsburgh area indicated that about 50 per cent of the cases had less than 10 per cent of the noise as measured at the factory, induced in the antenna and 75 per cent of the cases had less than 18 per cent of the factory noise induced in the antenna. From actual tests, made with the radio receiver in operation, 5,500 microvolts on the supply lines caused no interference to programs in 50 per cent of the cases. Where the better antenna installations were found, the antenna pickup was less than 2 per cent of the factory noise. Such installations gave no interference to programs with 50,000 microvolts on the supply lines. It was proved conclusively that the coupling of the antenna lead in and ground, with the service wiring is a very important factor in noise reduction.

These tests indicated that a good antenna system is essential if a really successful fight is to be made against radio interference in the home. Unfortunately, the radio distributor is more interested in selling the set than in keeping it sold. Accordingly it has been left pretty much up to the consumer to either buy an antenna installation or put it in himself. The utility which supplies the power to run the set, is very much interested in keeping the set sold, as loss of revenue occurs when the set is not in operation. From the utility standpoint, it is more important that the radio dealer sell the consumer, first a good antenna system and, second, a radio set, for it is to the utility the consumer complains in case of interference. From experience it has been found that the best remedy for interfering household appliances is a modern, scientifically designed and properly installed antenna system.

Where interference from household appliances cannot be reduced by installation of the best antenna possible, filters are usually applied on the electrical circuit of the interfering machine. In applying filters, two types of apparatus installations must be considered; (*a*) apparatus operated with the frame grounded and (*b*) apparatus operated with the frame ungrounded. When the frame is grounded, or ungrounded, the noise can best be reduced by placing capacitors of the proper size and characteristics, from each line to frame. Little noise reduction is obtained by connecting capacitors line to line and may even increase the noise output.

In the grounded case, the line to frame capacitors may be any value as they are connected direct to ground. In the ungrounded case, however, large capacitors cannot be connected to the frame because of the shock hazard. Suitable noise reduction is most effectively obtained by connecting two capacitors in series, line to line, and a third capacitor from the midpoint to the frame. The value of this third capacitor has been a much discussed problem for the past few years. If the value of the frame capacitor is too high the shock is very objectionable. The human body is sensitive to about 500 microamperes, so this capacitor must be held to a very low value —0.005 microfarads or smaller. If the filter is used in damp or humid climates the shock hazard is increased. The most serious problem comes in the possibility of the frame capacitor shorting out or failing. Then the shock hazard may endanger life under moist or wet conditions of the skin. In the case of the grounded machine, which may become accidentally ungrounded, the shock hazard is also serious, as the capacitors may be 0.1 microfarad or more. If, for any reason, more than one capacitor fails full line voltage may appear on the frame. Then the condition is dangerous to life.

To be an effective remedy for all appliance ills, it is readily seen that all manufacturers would have to filter their devices. Immediately the question arises, "Who shall pay for making the appliances interference free?" It has been stated that with a good antenna system, considerable interference voltage is not objectionable in an appliance. If the filter is compulsory, on many of the cheaper household appliances the filter cost may be a large proportion of the total cost of the article, as, for instance, the 10¢ store variety of egg beater, which sells from 69¢ to $1.00. Addition of a filter to such a cheap article may make the price prohibitive for the quality of the article. Where the cost of the filter is only a very small part of the total cost of the appliance, the problem is simply one of absorbing the cost of the filter in the selling price.

Another complication to the problem is that not all of the appliances of a group produce serious interference. Out of 1,000 high-grade appliances only 1 per cent may cause objectionable interference. There is a probability that not all of this 1 per cent will find their way into locations where interference will cause trouble. The same may be said of cheaper appliances, but the percentage of interference producers per thousand may be much higher. In some cases, a simple change in design may eliminate a part or all of the intereference trouble of a group of appliances.

Mass production of a complete line of filtered appliances is a very involved manufacturing problem. It would require (*a*) redesign of the appliance to include space for a filter, (*b*) new dies, jigs, and tools for each class of appliance, (*c*) standardization of filters for production and renewal replacements, and (*d*) a special organization to design and test the filters and appliances. Such a program could only be reflected in the final cost of the appliance to the consumer.

Where the cost of the filter is a small part of the cost of the appliance, it may be economically feasible to apply filters. In fact, several large manufacturers do filter certain classes of their appliances. While the general interference problem is not helped much by such filtering, it is an asset to the manufacturer as it helps to keep the appliance sold. Such filtering reduces complaints on that manufacturer's equipment and promotes good will, which is the best intangible asset any company can have.

F. E. Sanford and **W. R. Weise**: Professor Osterbrock has offered a qualitative explanation of external cross modulation. This type of interference can well be made the subject of laboratory experiments and theoretical studies, to the end of obtaining an acceptable explanation, which will lead to solution and elimination. So far this type of interference is not common but it may be expected to increase with increasing signal strengths, which overcome some of the more common types of interference.

Mr. Smith suggests the need of more quantitative analyses of radio interference. Undoubtedly this will help, but we believe that exact measurements are of secondary importance compared to a general recognition of the problems and the value of a co-operative spirit among all of the groups concerned.

In the field of quantitative analyses, apparatus and levels of measurement are essential for the further alleviation of interference caused by appliances. Mr. Benedict has pointed out the present uncertainty in this field. The manufacturers of insulators and other equipment for transmission and distribution line use, have given a great deal of attention to this and as a result the electric utilities can purchase equipment which is inherently "radio interference free." As pointed out in the paper, a similar interest in this subject is in order, on the part of the numerous appliance manufacturers. Many are now following along these lines, but many others apparently are not. In time the public will surely recognize freedom from radio interference possibilities, as a desirable feature of any appliance purchased.

Determination of the permissible level rather than the complete elimination of all radio interference must be the aim in the work to be done. A standardization of methods and technique, as is being attempted by the joint EEI, NEMA, RMA committee, is an important step in the direction, as pointed out by Mr. Bellaschi. Manufacturers who have considered the interference possibilities of their products are to be complimented and encouraged.

In conclusion, we feel that this paper justifies itself to the extent that it serves to further focus attention on the radio interference problems yet to be solved. The discussion, both written and verbal indicated that there is wide interest in the subject.

Analysis of Series Capacitor Application Problems

Discussion and author's closure of a paper by J. W. Butler and C. Concordia published in the August 1937 issue, pages 975–88, and presented for oral discussion at the power transmission and distribution session of the AIEE Pacific Coast convention, Spokane, Wash., September 1, 1937.

E. C. Starr (Oregon State College, Corvallis): The paper by Messrs. Butler and Concordia is a valuable contribution to the field of power transmission. The authors are to be complimented upon the breadth and thoroughness of their analyses of the principal difficulties encountered in the application of series capacitors to transmission circuits.

The series capacitor offers an almost ideal means of improving the voltage regulation of transmission circuits. The action is instantaneous and line reactance, together with the transformer and generator reactances, can effectively be cancelled. The result should be not only that of eliminating the reactance component of system voltage drop but should also be that of improving the steady-state stability limit of the system.

A few series capacitor installations have at first been more or less unsuccessful. These have cast some doubt over the practicability of their use due to one or more of the characteristic troubles, analyzed by the authors, having arisen in their operation. In applications involving large induction- and synchronous-motor loads, where an attempt has been made to completely compensate, or in some cases overcompensate, for line and transformer reactances, serious surging difficulties have arisen. In other applications, where a large part of the load is of resistance character, and in cases where overcompensation of system reactance was not attempted, the success of operation has been complete.

From a very approximate analysis it can be shown that a simple criterion for the successful application of series capacitors to circuits involving large synchronous and induction machinery is to avoid any attempt at complete or overcompensation. That is, the series capacitive reactance in such circuits should not be made equal to or greater than the combined inductive reactance of the line, transformers and generators involved in the particular circuit in question. This is a very simple criterion and no attempt will be made at this time to carry it to a more exact solution. In some cases it will be objectionable because it does not permit of the complete cancellation of system reactance or in the effective compensation for both resistance and reactance as is possible under some limited conditions.

Reference to figure 1 of this discussion will bring out two interesting features. It will be noted that for any normal load current, *I*, the sending-end voltage, E_1, is ahead, in phase position, of the re-

E_1 = Sending-end voltage (E_1')
E_2 = Receiving-end voltage
I = Line current
θ = Voltage angle between ends of line (θ')
R = Line resistance
X_L = Line reactance (inductive)
X_C = Series capacitor reactance

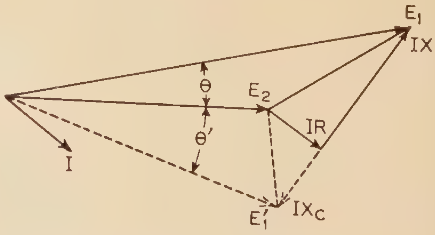


Figure 1. Simple transmission-line diagram

ceiving-end voltage, E_2, by the angle θ. Any increase in the load current, I, is accompanied by an increase in the angle θ, and up to a certain limit the system is stable. If a series capacitor is introduced in the system with capacitive reactance greater than the system inductive reactance, then the dotted line diagram will apply. It will be observed that no change has taken place in the system resistance drop, IR, but that the sending-end voltage, E_1', is smaller in magnitude when compared to E_2 than previously. This indicates the desired improvement in system voltage regulation. It will be noted, however, that the sending-end voltage, E_1', now *lags* the receiving-end voltage, E_2, by the angle θ', and any increase in the load current, I, will cause a further lag of E_1' behind E_2. This means then that if we assume E_1' to be supplied by an infinite bus or by a generator of relatively large rotational inertia, the receiving-end voltage, E_2, will be governed in phase position by the line current, I_1, an increasing current meaning an *advancing* phase position.

This condition is inherently one of instability. If, for example, the load consists of a synchronous motor and a sudden increase in delivered torque should occur, then the load current, I, would increase correspondingly and the terminal voltage, E_2, would advance somewhat in phase. This momentary advance of E_2 would tend to accelerate the rotor of the motor and again increase the current drawn by the motor from the system. This further increase of current would tend, again, to increase the angle θ'. However, as soon as the rotor had accelerated to accommodate the new phase position of the terminal voltage, the current would drop off somewhat, allowing the phase of E_2 to drop back. The rotor would then drop back in phase position and the current momentarily would decrease. As soon as the rotor had reached its normal load angle, the current would have returned to normal and would again be changing in the upward direction, starting to repeat the cycle of oscillation just described. An unstable surging condition is thus established which involves the complete mechanical as well as electrical system.

The same general analysis can be applied to an induction-motor load. In that case, a suddenly increasing load produces an increased slip which in turn increases the line current and causes the phase of its terminal voltage to advance momentarily. This advance in terminal voltage is the equivalent of a momentary increase in frequency resulting in increased instantaneous slip and hence in a further increase of line current. The rotor then tends to accelerate under the influence of increased current, and thus again starts the oscillation described above.

A very crude analogy is the case of a differential-compound motor driving a cumulative-compound d-c generator. An increase in load on the generator tends to increase slightly the speed of the motor which immediately increases the voltage of the generator and automatically causes it to deliver more load. Such a system, when adjusted for a small degree of overcompounding, will tend to oscillate and surge rather badly. If, however, the overcompounding is excessive, particularly in the case of the motor, the system will surge beyond control.

It can be said in general that, so long as the receiving-end voltage of an electrical system tends to *fall back* in phase with respect to the sending end with increase of load, any oscillations set up externally will be subjected to a definite decrement due to system resistance and machine friction, and the operation will be stable up to the limit of the system. If, however, the receiving-end voltage tends to *advance* in phase with respect to the sending end with increase of load, the system is inherently unstable and a surging condition can develop when rotating equipment is involved.

In most practical systems, particularly those involving a fairly large percentage of resistive loading, a small negative angle will give rise to no difficulties. Hence it is possible to compensate for all, or nearly all, of the system reactance by means of series capacitors without introducing any abnormal operating conditions. However, if large rotating machines are involved in the load, it is not advisable to overcompensate for the system reactance in order to obtain an idealized voltage-regulation condition.

In designing a series-capacitor installation, the load should be carefully analyzed from the standpoint of size and types of rotating machines involved and the power factors encountered. Where large machines are involved in the load, the capacitive reactance should be limited to a value which will not cause the terminal voltage of the machines to advance with respect to the sending-end voltage more than a few per cent of the normal load angle of the machines. It is realized that the voltage-regulation improvement to be obtained by the application of series capacitors is limited by these conditions, but a very large improvement can be produced by their use and further applications should be greatly encouraged.

J. W. Butler and **C. Concordia:** We wish to thank Professor Starr for his remarks and explanation of the phenomena of self-excitation on the basis of a simple vector diagram. We feel however that in general it will not be feasible to compensate to as great an extent as is indicated by his criterion. As brought out in the paper, one cannot compensate for the total effective steady-state system reactance; even the short circuit or transient reactance can usually be only partly compensated, perhaps half-way compensated. Figures 10 and 12 illustrate this point and show the limits for a particular set of system constants.

Relay Operation
During System Oscillations

Author's closing discussion of a paper published in the July 1937 issue, pages 823–32, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937. Other discussion of this paper appeared in the December 1937 issue, pages 1513–14.

C. R. Mason: Mr. Neher has described an extremely valuable method for studying relay operations under abnormal system conditions. His suggestion for applying that method to the problems of this paper merits further consideration. By this method one can determine the operating tendency of various relays quickly, accurately, and with a minimum amount of calculation if he has the conception of the elements of the problem which the paper attempts to provide.

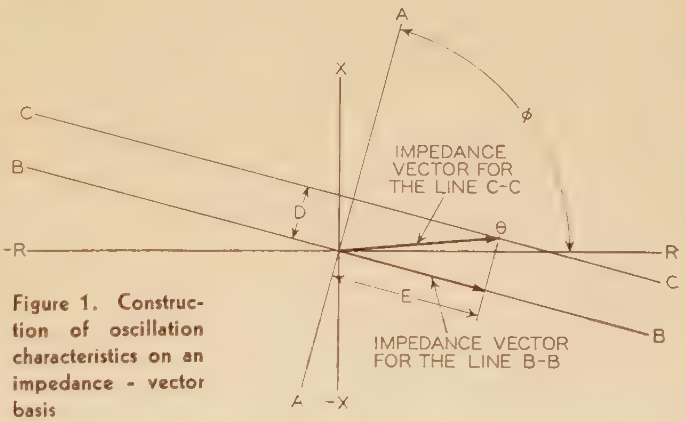

A
X
C
ϕ
B
IMPEDANCE VECTOR FOR THE LINE C-C
D
θ
-R
R
C
E
B
IMPEDANCE VECTOR FOR THE LINE B-B
A
-X

Figure 1. Construction of oscillation characteristics on an impedance - vector basis

Characteristics of a System Oscillation

The relations of current, voltage, and the angle between them can be conveniently represented on a two-dimensional picture by showing the ratio of the voltage to the current vectorially. Consider figure 1. Lay out the resistance and reactance axes to the same scale and draw the line *A-A* through the origin at the system phase angle ϕ to the resistance axis. Draw the line *B-B* through the origin perpendicular to *A-A*. The line *B-B* applies to the impedance center of the system. At that point the current is always at the same angle to the voltage regardless of change in the displacement angle θ. The impedance vector will always lie on this line, terminating at the dis-

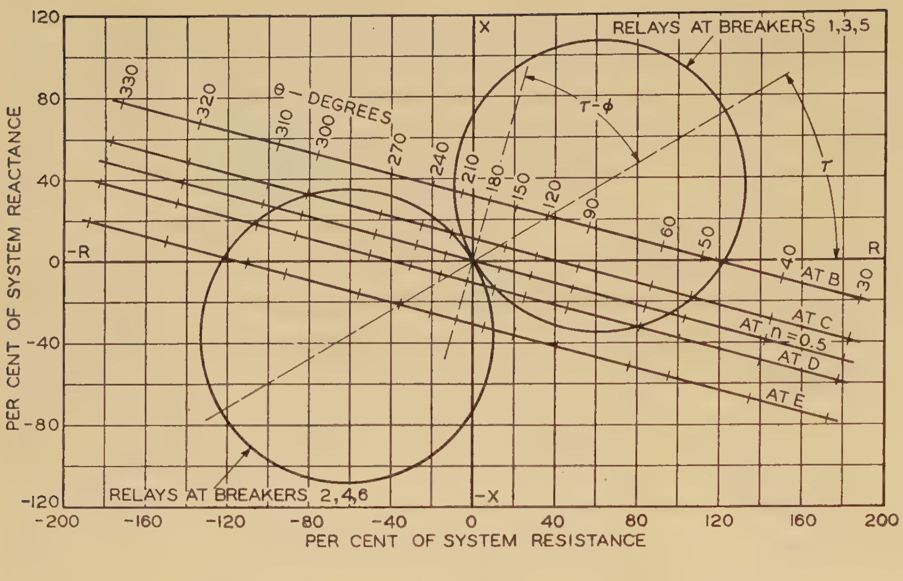


Figure 2. Voltage-restrained directional relay operating charactertistics combined with the oscillation characteristics to show relay operation

tance E to the right of the origin for any angle θ less than 180 degrees according to the relation $E = 50 \cot (\theta/2)$ where E is expressed as a percentage of the total system impedance. When θ exceeds 180 degrees, E will be measured to the left of the origin.

For some other point in the system toward the end, which in the paper was labeled "source A," the line C-C will apply. This line is parallel to the line B-B and at a distance D which is the per cent of the total system impedance that the point is from the impedance center of the system. For another point at the other side of the impedance center, the parallel line should be drawn on the other side of B-B.

Having determined θ for desired values of E or vice versa, according to the relation given for the impedance center line B-B, this same E and θ will apply for any other line if measured from the intersection of A-A and that line. In other words, as θ increases from zero, the head of the impedance vector for each location will move from right to left along its line, the heads of all of the vectors terminating on a line parallel to A-A as shown on figure 1. If source A starts in phase with source F and then goes lagging, the impedance vectors trace the lines from left to right.

Operation of a Directional Relay With Voltage Restraint

The relay diagram shown by Mr. Neher in his discussion of the paper is for a directional relay with different constants than that used as an example in the paper. Figure 2 shows the picture for the relay assumed in the paper having a three-phase minimum pick-up current of 7.0 amperes at 115 volts at its angle of maximum torque. The impedance pick-up of the relay at its maximum torque angle is therefore $V_A/7$. Since the system impedance is $2V_A/20$ according to the assumptions used, the relays' impedance pick-up is 10/7, or 143 per cent, of the system impedance at the angle of maximum torque. The relay circle is shown according to Mr. Neher's methods with its center on a line through the origin at an angle $(\tau - \phi)$ from the line A-A of figure 1, or at the angle τ from the R-axis. The diameter of the circle is 143 per cent of the total system impedance as previously determined.

Two circles are shown to account for the fact that the relays at breakers 2, 4, and 6 face in a direction opposite to the relays at breakers 1, 3, and 5.

For values of θ for which the oscillation line lies within the circle, the relay will operate to close its tripping contacts. If figure 2 is used to determine the point at which the relay changes its direction of torque, it will be noticed that slight errors in the curves of the paper are exposed. These curves were drawn from calculated data using the formulas of the paper, and during the process some error was introduced. A careful recheck of these calculations show that the errors are in the calculations and not in the formulas themselves. The fact that such a quick and easy check is possible using Mr. Neher's methods further emphasizes their value.

Figure 3 shows the circles for the voltage restrained directional unit of an actual distance relay which has a minimum pick-up ad-

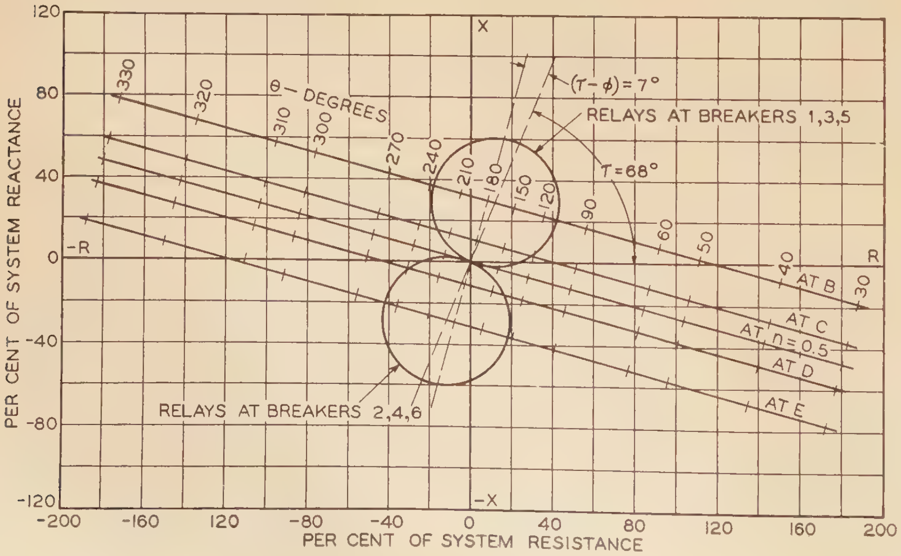
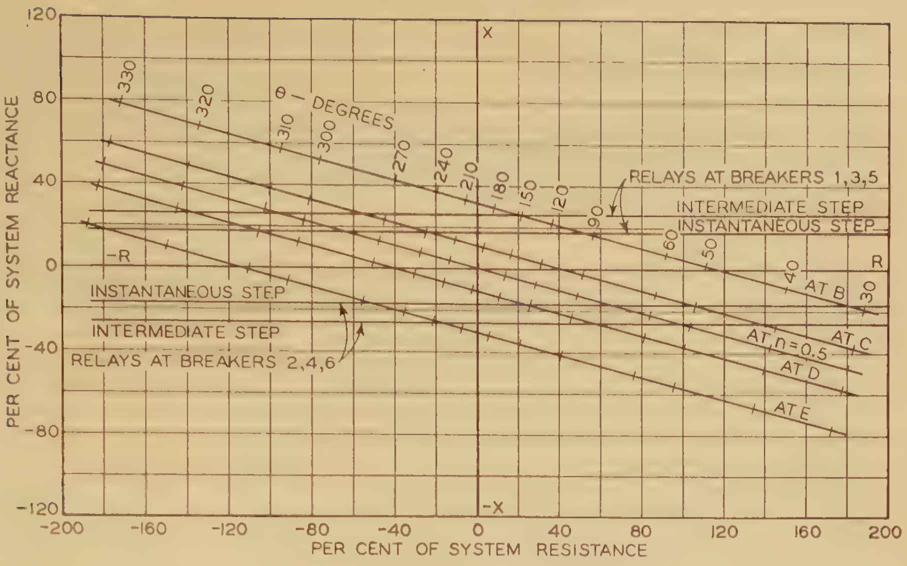


Figure 3. Combined oscillation and relay characteristics for an actual distance relay starting-element

Figure 4. Reactance element operating characteristics combined with the oscillation characteristics to show relay operation



justable to 16 amperes at rated voltage and at its angle of maximum torque (68 degrees). The diameter of this circle is thus seen to be 10/16 or 62.5 per cent of the system impedance; and $(\tau - \phi) = 7$ degrees.

Operation of a Reactance Relay

In figure 4 the operating characteristics of a reactance element adjusted as assumed in the paper are combined with the oscillation impedance characteristics. The operating characteristics of the reactance element are perpendicular to the X axis and intersect it at a distance from the origin which is the per cent of the total system impedance below which the element is adjusted to operate. The element operates to close its tripping contacts when the oscillation impedance vector terminates on the origin side of the relay characteristic. Here, as in the case of the voltage restrained directional relay, the characteristics for relays which face in opposite directions are drawn on opposite sides of the origin. These curves give a very accurate check of the curves in the paper.

Operation of an Impedance Relay

The characteristics of the impedance relay used in the paper are drawn in figure 5, together with the oscillation impedance characteristics. The radius of each curve is the per cent of the total system impedance below which the relay will operate. When the oscillation impedance vector falls inside of a circle the relay operates to close its tripping contacts.

Other Types of Relays

The characteristic of a directional relay without voltage restraint will be a straight line through the origin at right angles to the τ axis shown on figure 2. All oscillation impedance vectors to the right of this characteristic will cause the relays at breakers 1, 3, and 5 to close their tripping contacts; all impedance vectors to the left of the characteristic will cause the relays at breakers 2, 4, and 6 to close their tripping contacts.

The characteristics of single-quantity relays such as overcurrent, and undervoltage types cannot be shown on the diagrams, but their operation is easily determined otherwise.

Errata

In figure 12 *b* on page 828 the curves are incorrectly labeled. The curve labeled "At Breaker 4" applies to the relay at breaker 3 and the curve labeled "At Breaker 3" applies to the relay at breaker 4.

In the appendix under "Derivation of Equation 7" on page 832 there is an I missing in the denominator of the first expression. It should read:

$$Z = V/I$$

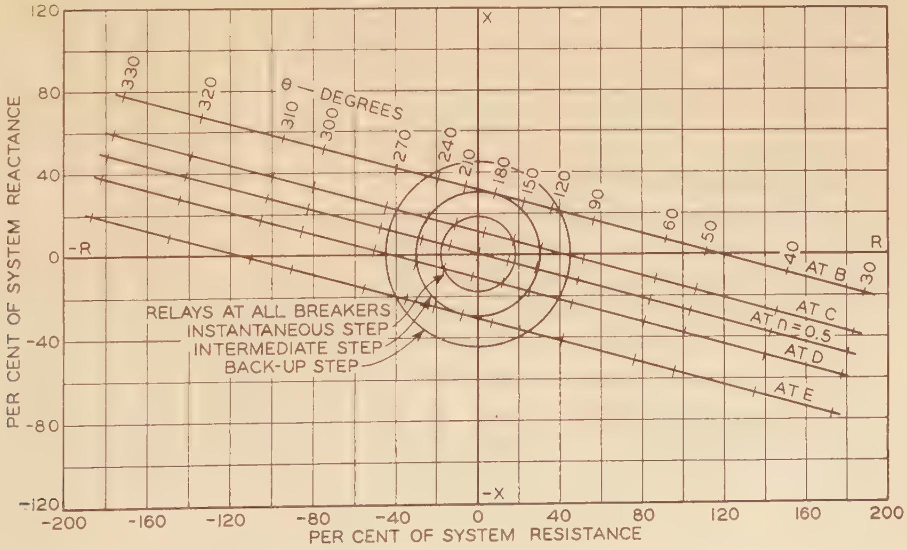


Figure 5. Impedance relay operating characteristics combined with the oscillation characteristics to show relay operation

Carbon Brushes for Steel-Mill Equipment

Discussion and author's closure of a paper by W. C. Kalb published in the September 1937 issue, pages 1165–8, and presented for oral discussion at the iron and steel session of the AIEE Middle Eastern District meeting, Akron, Ohio, October 15, 1937.

L. E. Miller (The Reliance Electric & Engineering Company, Cleveland, Ohio): I am very glad to see Mr. Kalb bring out in his paper the fact that the same type of brush may be satisfactory under one certain set of conditions, but under other conditions may be entirely unsatisfactory. I feel that the corollary to this is that no type of brush is a satisfactory cure-all for any and all conditions under which the brush may be required to operate. I think that this point should be particularly emphasized, since it has been my experience that often times some particular brush is given to an operator to cure a certain specific set of conditions, and does its job so successfully that the operator desires to use this particular brush for every and all kinds of conditions. The result is many misapplications, causing endless difficulty, expense, and dissatisfaction.

Mr. Kalb, in speaking from notes, quoted from Doctor Glass's paper which occurred in an earlier issue of the *Iron and Steel Engineer*. While Mr. Kalb did not mention in his talk, I believe that Doctor Glass brings out the idea that the film on the commutator which gives the glossy chocolate-brown surface so desired, is a form of oxide in copper. This film, as a rule, is only produced after considerable operation of any particular machine. I would like to ask Mr. Kalb if there has been any experimental work done with the idea of producing this film quickly in any other way than the usual method of operating the machine.

W. C. Kalb: In reply to Mr. Miller's question, it is mentioned in the paper by Doctor Glass, to which reference is made, that the application of methyl alcohol as a reducing agent on a test commutator, operating with lampblack base brushes at an interface temperature of 125 degree centigrade caused the coefficient of friction to rise to 0.5. The application of hydrogen peroxide immediately brought the coefficient of friction down to 0.13, the normal friction, at 125 degree centigrade, of the grade being tested. In applying these reagents the brushes were lifted from the commutator and excess of the reagent was removed before replacing the brushes. Repeated trials gave the same results.

While this laboratory test indicates that a beneficial oxide film might be formed by the application of an oxidizing reagent to the commutator surface, I do not know of any instance where this plan has been tried in actual service.

Formation of oxide film can also be accelerated by the application of external heat to the commutator surface. It might be feasible for the electrical manufacturer to use this means for developing a commutator surface of the desired character before the machine leaves the factory, but the method does not seem well adapted to use in the field.

Transactions

Papers and Discussions Comprising Pages 115–70 of the 1938 Volume

An Electronic Arc-Length Monitor

By WALTHER RICHTER
MEMBER AIEE

IN THE March 1935 issue of *Electronics*, a voltmeter for d-c arc welding was described. In this instrument the arc voltage was applied over a high resistance to the grid of a vacuum tube and a condenser was shunted across grid and cathode. The rapid fluctuations of the arc voltage are filtered out by this combination, and a meter placed in the plate circuit of the tube can therefore be calibrated in terms of average arc voltage. It was also possible to spread the scale of the meter so that it covered the range of welding voltage only, which leads to an increase of accuracy in determining the average arc voltage.

The application of this instrument in the shop not only showed that different welders using the same electrode and amperage would weld with voltages differing as much as four volts, but also that some kept the arc voltage constant within one to two volts, while others covered a range of five to six volts during welding. Some electrodes will operate well over a fairly wide range of values, but others were found to give decidedly inferior results when the welding voltage deviated as much as three volts from the value determined in the laboratory. The instrument described above permits a bystander to observe the performance of an operator, or it can be used to adjust the arc length held by an automatic weld head to the correct value, but it cannot be read by a hand welder since he must keep his eyes at all times on the arc. It therefore seemed desirable to have an instrument which would inform the welder about the voltage on his arc without requiring that he look away from the arc.

Acoustical means were considered first, but were found undesirable for several reasons. In the instrument described in this paper the problem is solved in the following manner: Two small flashlight bulbs are mounted in the welding shield or hood, one on each side of the window through which the welder looks at the arc. The circuit to which the bulbs, as well as the arc, are connected contains a potentiometer bearing a calibration in volts. This potentiometer can be set to any desired value, say 35 volts. If the average arc voltage is held to 35 volts, both bulbs will be extinguished; if the voltage rises to 36 volts the right bulb starts to glow faintly, increasing in brilliance with an increase in deviation; if the arc voltage falls below 35 volts, the left bulb acts in the same manner. The maximum brilliance is kept well below the point of hurting or blinding the welder's eyes. He can keep his conscious attention entirely on the arc, yet will be able to notice a surprisingly faint glow out of "the corner of his eyes" and can therefore immediately correct the deviation from the desired condition.

The principle of the circuit by means of which these results are obtained is the following: The arc voltage or a part thereof is connected in opposition to an adjustable d-c voltage. The resulting differential voltage is filtered by a resistance-capacity combination, leaving only the average difference. By means of an electron tube an alternating voltage is next produced with a magnitude which is a function of the above mentioned filtered differential voltage: it is zero, when the differential voltage is 2.5 or more, about ten volts, when the differential voltage is 1.5 volts, and about 20 volts, when the differential is 0.5 or less. This alternating voltage, varying between zero and 20 volts as just outlined, is now connected in series with a fixed alternating voltage of ten volts, but of opposite phase. The sum of these two voltages is obviously a new alternating voltage, which not only changes in magnitude but also reverses in phase; it will be zero, when the differential d-c voltage is 1.5 volts. This new alternating voltage is fed into the primary winding of a transformer, the secondary of which is center-tapped. The two sections of this winding and the bulbs in the welder's helmet form a bridge arrangement, and between the center tap of the transformer and the junction of the bulbs a fixed alternating voltage is introduced. The current produced by the latter in the two bulbs is adjusted by means of a variable resistor to a value just below the point of glowing. A voltage induced in the secondary winding of the center-tapped transformer will then obviously increase the current in one lamp and decrease it in the other, depending on the phase of the induced voltage. Since this voltage, as explained above, changes in magnitude as well as phase, either one or the other bulb can be made to burn with a change of the arc voltage. The value of arc voltage at which both bulbs will be extinguished can be set by changing the adjustable d-c voltage opposing it.

Paper number 37-140, recommended by the AIEE committee on electric welding and the joint subcommittee on electronics, and presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted September 24, 1937; made available for preprinting December 7, 1937.

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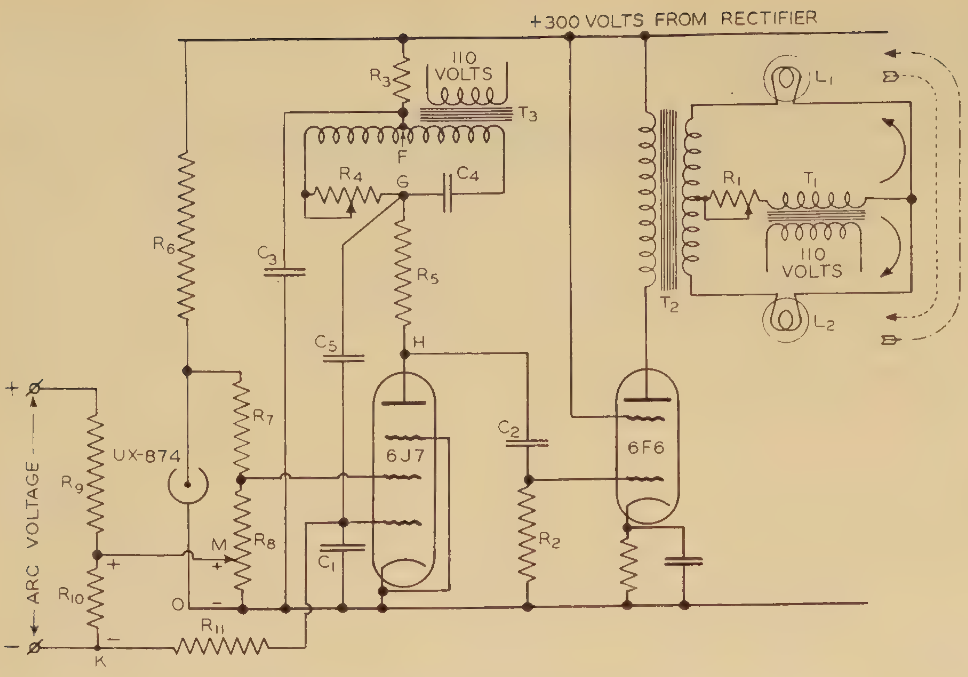

Figure 1. Diagram of arc-length monitor

The circuit putting the principle outlined above in practice is entirely electronic. It employs two amplifier tubes, a 6*J*7 and a 6*F*6, the first acting as voltage amplifier, the second as output tube. For simplicity the rectifier system, which is of the conventional type, as well as heater connections of the tubes are not shown in the diagram, figure 1. Voltage divider R_9 R_{10} is connected across the arc and the part of the arc voltage appearing across R_{10} is connected to the arm *M* of potentiometer R_8. This potentiometer is calibrated in terms of arc voltage, and in order to make this calibration as independent as possible from line voltage fluctuations, the current through R_8 is held constant by shunting voltage regulator tube *UX*874 across R_7 and R_8. The difference between the voltage *OM* over the lower part of potentiometer R_8 and the voltage *KM* across R_{10} is used as the d-c grid bias on the first tube. Resistance R_{11} which is 500,000 ohm and condenser C_1 of one microfarad capacity serve as a filtering element, so that the grid bias of the tube depends only on the average arc voltage. The production of an alternating voltage depending in magnitude on the d-c voltage is accomplished by applying a small alternating voltage to the grid of the first tube and changing the amount of amplification by changing the d-c bias voltage. The alternating voltage is obtained as follows: Point *G* has an alternating potential with respect to *O* of about ten volts. Condensers C_5 and C_1 act as a voltage divider; the capacity of C_5 is only about 0.025 microfarad, so that only a small alternating voltage appears on the grid. The amplified voltage will appear across the load resistor R_5 in the plate circuit of the tube, but the degree to which the tube will amplify the alternating voltage applied to the grid will depend on the d-c grid bias. In this particular circuit the 6*J*7 will cease to amplify when the negative grid bias exceeds 2.5 volts; with a negative grid bias of 1.5 volts, the alternating voltage appearing across the resistor R_5 will be ten volts, while with a negative grid bias of 0.5 volts or less the tube reaches full amplification, and the output voltage will be 20 volts across R_5. However, the alternating voltage drop across R_5 is only one part of the total alternating potential of point *H*, which is applied to the grid of the output tube by means of conventional capacity coupling C_2R_2. The other part is the alternating voltage *FG*, obtained from a center-tapped winding of transformer T_3. Resistor R_4 and condenser C_4 are connected across this winding, and since the voltages across R_4 and C_4 are always 90 degrees out of phase, a variation of R_4 will change the phase but not the magnitude of the voltage *FG*, which will always be one-half of the total voltage produced in the center-tapped winding at T_3. In this particular case the voltage *FG* is ten volts. The phase adjustment of this voltage is necessary to obtain proper balance in the final bridge circuit containing the bulbs. Due to the filtering effect of the resistance capacity combination R_3C_3, point *F* has no alternating voltage against O. As we had seen above, a small part of the alternating voltage *FG* was applied to the grid of the 6*J*7 by means of the voltage divider C_5C_1, and since any amplifying tube also produces a phase reversal, the output voltage *GH* will be 180 degrees out of phase with the voltage *FG*. This can be seen in another way: Consider the instant when the potential of point *G* has reached its negative maximum with respect to point *F*. Due to the voltage divider C_5C_1, the grid of the 6*J*7 will also reach its negative maximum at this instant.

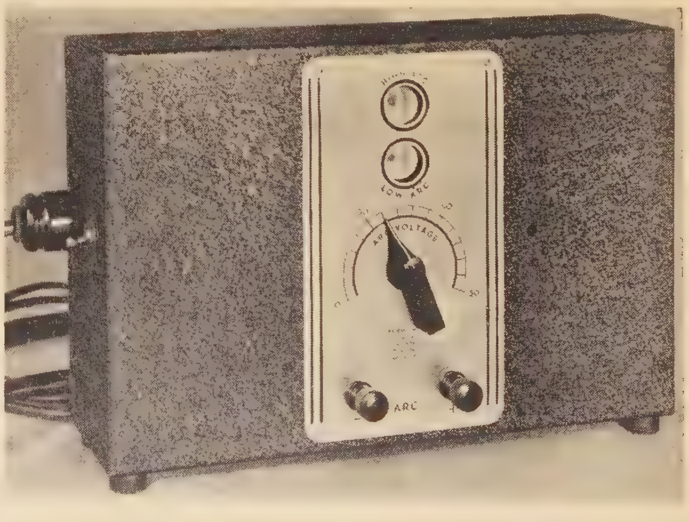

Figure 2. Front view of arc-length monitor

The alternating component of the plate current will then reach its minimum and with it the voltage drop across R_5. At this instant point H is therefore the least amount negative with respect to point G, and is seen to be 180 degrees out of phase with the potential of point G. When the alternating voltage across R_5 is just ten volts, the alternating potential applied to the grid of the 6F6 will be zero, since then the voltages FG and GH add up to zero. It is therefore seen, that as the arc voltage varies in such a manner, as to change the resulting negative grid bias on the first tube from 2.5 volts or more to 1.5 volts and finally to 0.5 volts or less, there will appear on the grid of the 6F6 an alternating voltage of 10 volts, which will diminish to zero and then build up again to 10 volts in opposite phase. Phase control of this voltage is obtainable by adjusting R_4. Incidentally, this system of converting a small d-c voltage change into a phase reversing alternating voltage can also be used where grid control of mercury vapor rectifiers (thyratrons) is desired from a small d-c voltage change. In the plate circuit of the output tube is found transformer T_2, the center-tapped secondary of which is connected in a bridge circuit containing lamps L_1 and L_2. The low-voltage winding of transformer T_1 is connected between the center tap of T_2 and the junction of the bulbs, and the current produced by it will flow at a given instant through the bulbs in the direction of the arrows drawn in full lines. The magnitude of it is adjusted by varying R_1 to a value just below the glowing point of L_1 and L_2. Grid excitation of the 6F6 will produce currents in the bridge circuit in the direction of the arrows in dotted or dash-dotted lines, depending on the phase of exciting alternating voltage on the grid. In the case of the dotted arrow the current through L_2 will be increased, through L_1 decreased, while the reverse takes place in the case of the dash-dotted arrow. The output of the tube is sufficient to operate more than one set of lights and on the finished instrument, figure 2, a second set of lights is provided which can be observed by the foreman or superintendent.

The results obtained with the instrument are very satisfactory. In training men, it was found that new men acquired the ability to hold a steady arc in about one-third of the time that it took without the instrument. The biggest advantage comes from the fact that all men could be trained to the technique best suited for the particular electrode. In one case the electrodes required for the work had to be welded within narrow limits of voltage. All work was X-rayed and any defects had to be chipped out and rewelded. After equipping the operators with these instruments the necessary repair work dropped to a fraction of what it was before. In this connection it was interesting to note that relatively new men produced good work sooner than old welders. It was obviously easier to acquire the correct method right from the start than it was to break away first from a faulty habit. Men that have been trained with bare-wire welding as a rule try to hold as short an arc as possible, which usually is undesirable for coated electrodes. With the aid of the instrument, men with this type of training could be switched over to coated electrode welding considerably faster than ordinarily.

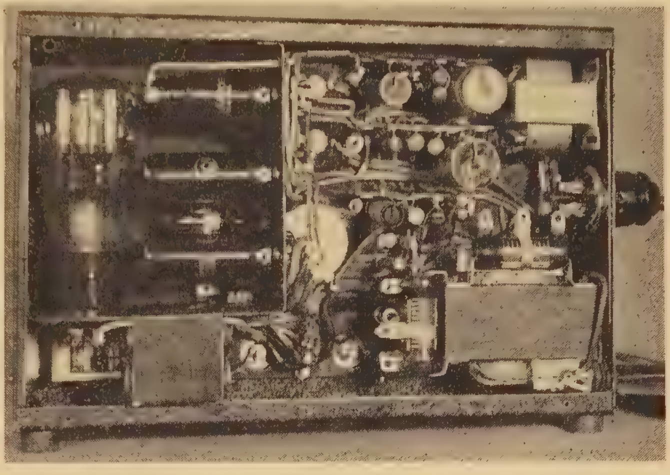

Figure 3. Rear view of arc-length monitor, back removed

The Application and Performance of Carrier-Current Relaying

By PHILIP SPORN
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I. Introduction

THE GENERAL idea of pilot relaying is quite old. It has been employed for several decades in the Mertz Price system where pilot wires are employed for balancing the currents at the two ends of the line and has met with considerable success in Europe, and particularly in England. A simpler pilot scheme in which the pilot wire is used merely to conduct an impulse, and the conditions of the line at the two ends of the section are indicated by the relative positions of a series of power directional relays, has been employed and has been described elsewhere.[1] Neither of the above schemes, however, has ever met with any great favor in the United States on account of the prohibitive cost of pilot wire circuits, and particularly on long lines, and because in the long run the scheme itself is no more reliable than the pilot wire. Experience has shown that the reliability of the latter is not quite at the 100 per cent level desired and mandatory for proper service.

One attempted solution for this difficulty was the substitution of carrier current for the pilot wire. A scheme embodying the idea was developed several years ago by Fitzgerald and is fully described in a paper before the AIEE.[2] The weakness of this scheme and the development of the first effective carrier relaying system as well as its performance in practical operation have been previously discussed.[3] This latter system was entirely successful but its operating speed was limited due to the racing of contacts. In practice this meant the maximum reliable speed was limited to a minimum time of approximately four cycles in terms of a 60-cycle system. However, it soon became evident that it would be necessary to reduce the relay time as close to the theoretical minimum (in power directional relay practice one-half of one cycle) as possible. A more detailed discussion of this requirement and the work that eventuated in the development of the one-cycle carrier relay system which is now the accepted system has been given elsewhere.[4]

Although developments of this system or slight modifications thereof have been described in papers presented or being presented before the Institute,[5,6] none of them however, have heretofore given a detailed discussion of the basis of application of carrier and particularly high-speed (one-cycle) relaying. In view of the fact that the authors have been engaged in the work of development of carrier relaying and its application over the past 11 years, they hope to be able to give here an intelligent and comprehensive discussion of the principles of relay practice as applied to carrier, to outline what can be accomplished by its use, and to show actually how it has been applied and the way in which it performs. To this end the authors believe it will be helpful to describe briefly the actual carrier current relaying equipments which have proved highly successful in actual operation since their installation on the transmission lines of the various power systems with which they are associated.

A diagram of the first effective carrier current arrangement is shown in figure 1 and will prove of interest. It consists basically of one three-phase power directional relay without voltage restraint, three instantaneous overcurrent starting relays, three definite time overcurrent tripping relays and one receiver blocking relay. In case of an external fault the starting relays operate to close their contacts instantaneously at both stations. At the station where the power flow is from the line into the bus the directional relay opens its tripping contacts preventing the tripping relays from opening up the breaker. In addition the transmitter plate contacts of the directional relay close, starting carrier transmission at this station. At the other station, the power flow is of necessity from the bus into the line and the tripping contacts of the directional relay remain closed, thus not permitting the transmitter to operate. Carrier will be received by the receiver relay which will open up the trip circuit at this other station. In case of an internal fault the power flow

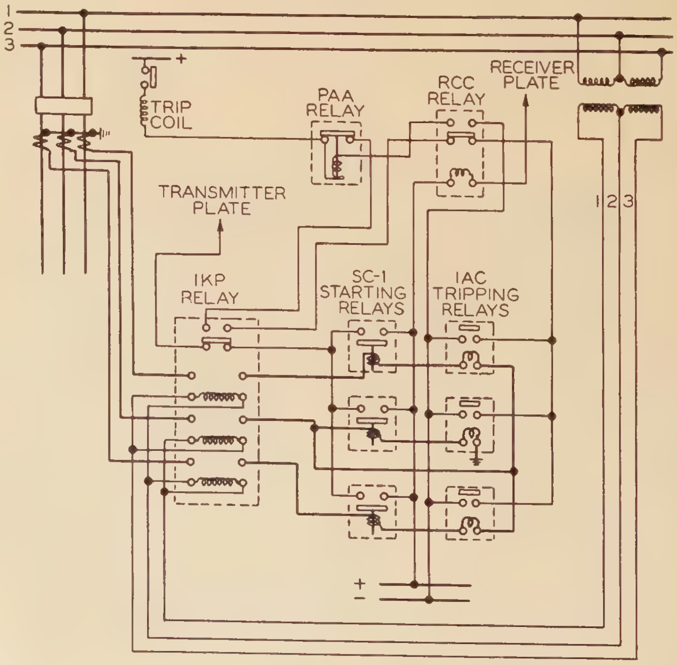

Figure 1. Four-cycle carrier-current relay arrangement

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[1] For all numbered references, see list at end of paper.

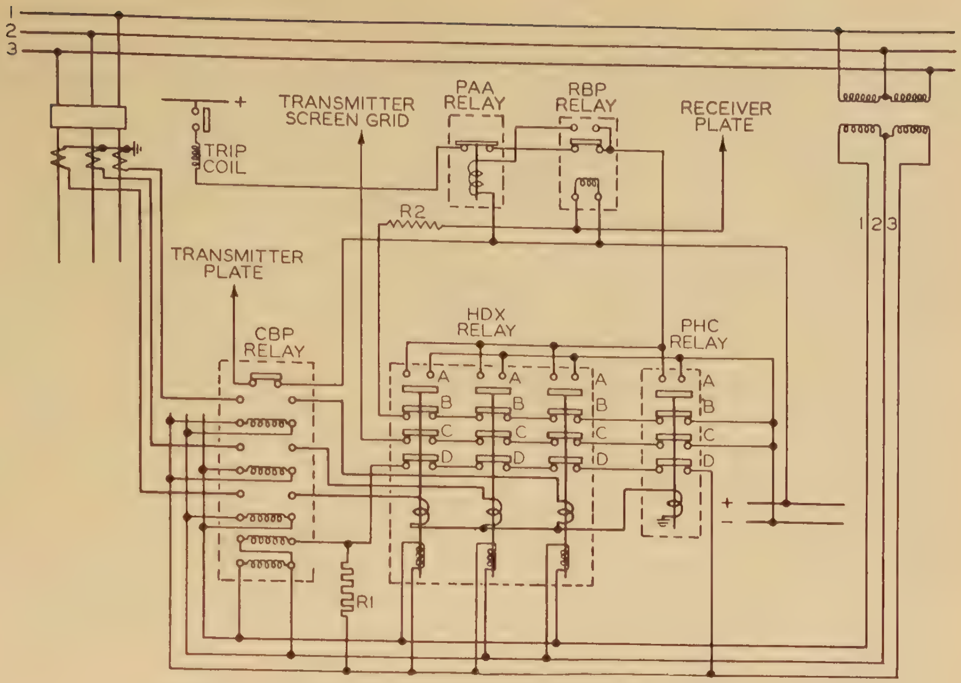

Figure 2. One-cycle carrier-current relay arrangement

at both stations will be from the bus into the line, hence the tripping contacts of the directional relays at both stations will remain closed and the transmitters will be inoperative. Therefore the tripping relays at both stations will close their contacts and trip their respective circuit breakers.

As already mentioned, this scheme was entirely successful except for the comparatively slow operation speed. The one-cycle scheme of protection is shown in figure 2. It will be seen that the outstanding feature is the employment of three simple multicontact instantaneous impedance-type phase relays in one case and one multicontact instantaneous ground overcurrent relay in combination with one three-phase power directional relay with voltage restraint and one receiver relay. All contacts of the instantaneous fault-detector relays are circuit opening except the tripping contacts which are circuit closing. This combination gives a circuit having the equivalent of a conrinuous carrier circuit, with the battery taking the place of carrier under normal conditions.

Under normal conditions the *CBP* directional relay contacts are held closed by voltage restraint applying plate voltage to the transmitter, but the transmitter does not operate due to the normally closed contacts *C* of the fault detector relays applying a negative bias to the screen grid of the transmitter. Further, the *RBP* receiver relay contacts are held open by the closed contacts *B* of the fault-detector relays energizing receiver relay coil from the station battery. In case of an external fault, the instantaneous fault detectors operate at both stations to remove voltage restraint from the directional relays, bias from the screen grid of the transmitters and local battery supply from receiver relay coils. The instant that the bias is removed from the screen grids the transmitters at both stations operate, thereby holding receiver relay contacts open. At the station where the power flow is from the bus into the line the directional relay contacts open, stopping the local transmitter from operating, but at the other station the transmitter is operating causing carrier to be received, preventing the receiver relay contacts from closing. After three cycles, the *PAA* lockout relay contacts at both stations open, to prevent the breakers from tripping on sudden reversals of power flow after the fault is cleared. Therefore at both stations the receiver relay contacts remain open, thus preventing tripping of the circuit breakers. In case of an internal fault the operation is similar except that the directional relay contacts will open at both stations, stopping transmission of carrier and causing the receiver relay contacts to close at both stations and trip their respective breakers.

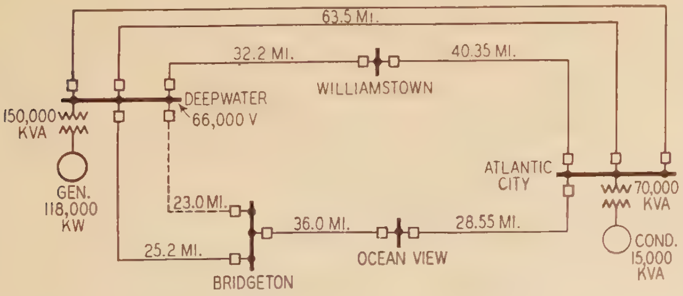

Figure 3. Illustrating problem 1: 66-kv system of Atlantic City Electric Company

II. Applications of High-Speed Carrier to a Power-Transmission System

In order to show the possibilities in the way of application of high-speed carrier relaying to the solution of either technically or economically difficult problems in the operation of high-tension power systems, a series of problems as they normally present themselves to the transmission designer or operator will be taken up and the use of carrier in their solution will be briefly discussed. Alternatives where such exist will be given and the advantages pro and con through the use of carrier will be pointed out.

PROBLEM 1. ADDITION OF ANOTHER STATION IN AN EXISTING TRANSMISSION LINE LOOP

Figure 3 is a typical existing transmission system loop which had been protected, adequately, until the change referred to below was carried through, by instantaneous overcurrent protection in conjunction with the standard time-delay reverse power protection. It is to be noted that the normal source of power flow is from Deepwater to Atlantic City, very little generation taking place at Atlantic City, but reactive corrective capacity running at Bridgeton and Atlantic City. Owing to the increased demands for transmission facilities, an additional circuit shown dotted in figure 3 was called for between Deepwater and Bridgeton. Further sectionalization, which at Ocean View had not been resorted to owing to relaying difficulties, now became imperative in order to protect service to the region served by the step-down station located at Ocean View.

In this particular case the standard solution would be to install balanced protection in conjunction with separate overcurrent or reverse power protection on the double circuit line between Deepwater and Bridgeton and go to reverse power overcurrent protection at Ocean View. This, however, would call for an increase in the time setting at Deepwater on the separate overcurrent relays and this, it was felt, would be intolerable in view of the fact that several important loads, very sensitive to voltage disturbances were being served at Bridgeton. The solution adopted, therefore, was the installation of one-cycle carrier protection between Bridgeton and Ocean View. Carrier here was the only practical solution.

It is to be noted in this case that no difficulties were taken into consideration from possibilities of double circuit faults between Deepwater and Bridgeton, in view of the fact that the two circuits between those two points run on different rights of way. But if this difficulty had to be considered, then the necessity of carrier on the section between Deepwater and Bridgeton would have had to be given serious consideration.

Problem 2. Prevention of Important Synchronous Motors Dropping Out of Step on Voltage Surges of Long Duration

Figure 4 shows the 44-kv transmission system of the Appalachian Electric Power Company radiating out from the Cabin Creek generating station. The Belle Substation supplies a large industrial chemical load of approximately 50,000 kw demand, which consists mainly of 2,000- and 2,700-horsepower low-speed synchronous compressor motors which are very sensitive to voltage surges. From extensive studies made, it was found that for any phase-to-phase fault occurring on this transmission system within an area of 20 miles of the Cabin Creek 44-kv bus, the synchronous motors at the chemical plant would drop out of step unless these faults were cleared within 10 cycles. The assurance that all phase-to-phase faults within this area would be cleared in this time could be obtained only by installing the one-cycle carrier current relaying in conjunction with high-speed oil circuit breakers on all the line sections indicated in figure 4. Again carrier offered the only practical remedy in a very difficult case. It is to be noted that no carrier current installation was necessary on the Cabin Creek-Charleston line. It was found that the instantaneous overcurrent relay protection on this line section would clear the phase-to-phase fault within a period of 10 cycles for all phase-to-phase faults that were likely to affect the stability of the motors at the chemical plant.

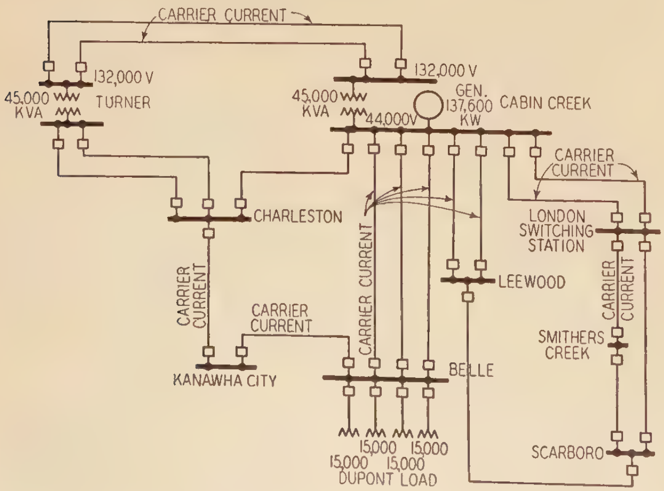

Figure 4. Illustrating problem 2: 44-kv system of Charleston division of Appalachian Electric Power Company

Problem 3. Stability of a High-Tension Transmission System

Figure 5 shows a 350-mile double-circuit tie line between the Philo station of The Ohio Power Company, the Twin Branch station of the Indiana & Michigan Electric Company, and the Michigan City station of the Northern Indiana Public Service Company. These three stations in turn tie in very extensive 132-kv networks totalling some 4,000,000 kw of generating capacity. On this tie line it was essential that all types of faults, such as, ground, phase-to-phase, and simultaneous faults on two circuits be cleared as rapidly as possible in order to keep within the stability limits of the tie line. In addition to high-speed oil circuit breaker installations, all the line sections with the exception of the short section between Twin Branch and South Bend stations were equipped with carrier current relay protection in addition to the standard schemes of balanced and instantaneous overcurrent protection. Only the carrier current system offered fast enough relaying in case of simultaneous trouble on two circuits and at the same time insured in case of either single-line or two-line faults that all breakers on the section in trouble would trip simultaneously. Cascading of oil circuit breakers would result in too slow clearing and would make the transmission system either inoperative or materially reduce its transmitting capacity.

This, of course, would be the case if an attempt were made to solve the problem through the use of a combination arrangement employing either instantaneous overcurrent or distance relays. In short, as has been pointed out before, carrier is the only practical solution that gives the necessary protection for an important sectionalized line like this and makes possible the utmost development of its transmitting potentialities.

Problem 4. Stability of Short Parallel Lines Radiating From a Large Generating Station

Figure 6 shows the short double-circuit lines radiating from the Philo generating station supplying Zanesville and

Crooksville stations. These 132-kv circuits are very short in length and when simultaneous faults occur on both circuits, the shock to the 132-kv system is extremely severe and results in opening the tie line between Philo and Twin Branch stations unless such faults are cleared very fast. For single-line faults occurring on either of these lines, high-speed clearing is obtained by the standard high-speed balanced schemes of protection. In case of simultaneous troubles on both circuits, the standard forms of relaying would not assure fast enough clearing under these conditions. Due to the infrequent occurrence of such faults, the cost of installing complete carrier current relaying equipment at all six terminals was not warranted. A scheme of carrier current relaying was therefore developed which would trip both oil circuit breakers at Philo station practically instantaneously only when a fault involving both 132-kv circuits occurred.

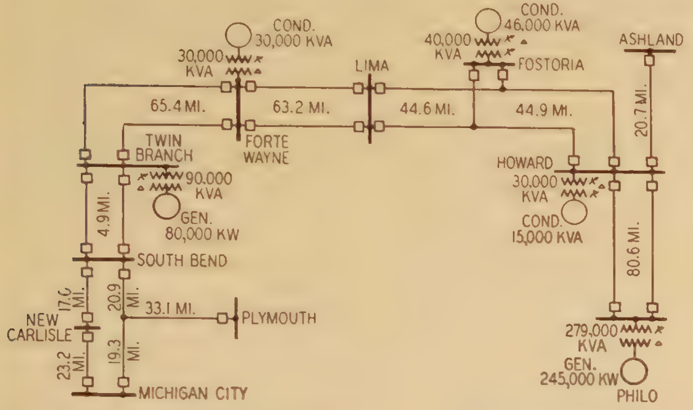

Figure 5. Illustrating problem 3: 132-kv double-circuit tie line of The Ohio Power Company and Indiana & Michigan Electric Company

Problem 5. Ultrahigh-Speed Reclosing

The development of the idea of ultrahigh-speed reclosing and its application, including the performance of the equipment, has been presented in a previous paper.[7] That paper described the installation of an ultrahigh-speed reclosing setup on a line of the Indiana & Michigan Electric Company. Figure 7 shows the transmission line in question including a number of connecting lines all of which comprise a 132-kv transmission loop circuit radiating from the Fort Wayne station of the Indiana & Michigan Electric Company and supplying the Deer Creek and Delaware substations of the Indiana General Service Company. Although there is an interconnection with Kokomo, it has not enough capacity to supply the entire load of the Indiana General Service Company when separated from Fort Wayne station under double-line-fault conditions occurring on the two lines from Fort Wayne. The load here, therefore, really represents the general condition of a stub load fed from an interconnected system either by a single line or by a double-circuit line on a single tower line. The continuity problem is typical of the problem such a load presents of maintaining uninterrupted service either under a single-line or a double-line faulting, respectively. The only inexpensive solution for this problem is ultrahigh-speed reclosing. A trial installation made a year ago on the Fort Wayne-Deer Creek line showed effective results in 75 per cent of the cases. Specifically, out of eight cases of faulting of the line between Fort Wayne and Deer Creek on all of which ultrahigh-speed reclosing took place, six definitely held on first reclosure and the other two resulted in the restriking of the arc necessitating retripping of the line.

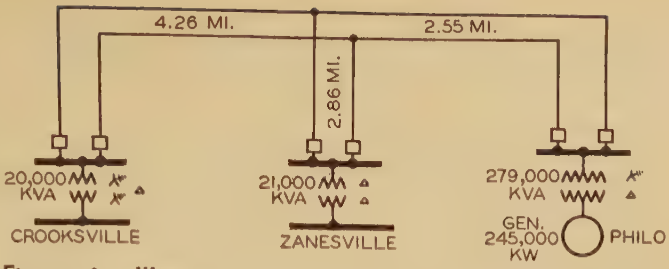

Figure 6. Illustrating problem 4: 132-kv short double-circuit line of The Ohio Power Company supplying Zanesville and Crooksville

It is obvious that this does not give a 100 per cent solution to the continuity problem but the fact that apparently 75 per cent of flashovers can be eliminated as far as the system effects are concerned is, the authors believe, without question a major contribution to the solution of the continuity problem on transmission-line operation.

In order to make high-speed reclosing practical, it was necessary to be able to re-energize the line not longer than 20 cycles after the initiation of the fault, and it was necessary to very definitely have a waiting time between arc outage and line re-energization of between 6 and 8 cycles. To accomplish this and to assure both breakers on the line operating simultaneously, it was necessary to have a one-cycle carrier-current system; any other arrangement would have given neither the speed of clearing nor the necessary interval between clearing and re-energization to get the beneficial effects of rapid reclosure.

The problem of the application of ultrarapid reclosing to high-tension networks to eliminate the effects of line outage and to improve stability limits of such networks is a very broad problem and one that will warrant further consideration and it is hoped to present a paper on that in the near future. It is interesting, however, to observe that in a case of a double-circuit tie between two systems such as the one represented by figure 5, studies have indicated that for single-circuit operation the amount of power that can be carried through a disturbance with rapid reclosure of the faulted circuit increases appreciably as the time of separation between the systems is decreased. This definitely points to the desirability of keeping the tripping and the reclosing time to a minimum even though the systems are large and the rate of decay of speed is slow. For double circuit operation with a clearing time of 12 cycles, it is possible to transmit 40 per cent more power with a successful rapid reclosure of the faulted circuit than if the circuit is not reclosed.

All of the above indicate a great many unexplored benefits from ultrarapid reclosure and ultrarapid reclosure is impossible of attainment without high-speed carrier relaying.

PROBLEM 6. THE GENERAL CASE—SUMMATION

In general it may be stated that high-speed carrier will solve economically the transmission problem wherever the following operating situations develop: necessity of speed and utmost reliability in the clearing of faults to accomplish minimum system disturbances; necessity of minimum disturbance to voltage sensitive equipment; need to bring up to a maximum load stability limits, either static or transient, of a transmission line; and the need of remedying the effect of line outage by ultrahigh-speed reclosure. In brief, whenever the necessity arises of counterbalancing the deleterious effects of system faults by the utmost speed in removing them from the faulted sections to leave the rest of the system undisturbed, or where high-speed reclosure of a faulted section is desired in a time so short that no ill effect of the initial fault results, the application of high-speed carrier relaying is imperative. As system concentrations increase and the injurious effects of system faulting correspondingly rise, the necessity of counterbalancing the deleterious effects of system faulting obviously increases.

III. Performance of Carrier Equipment

The discussion of the application developments given above shows, the authors believe, the wide application open to high-speed carrier relaying but after all, the theoretical benefits are of far greater significance if accompanied by actual performance experience. In this connection the experience of the authors on their own system is, therefore, pertinent. At the time of writing (October 1937) there are 34 carrier current relay terminal installations in operation on the transmission systems of the various companies with which the authors are associated. The first ten of these were placed in operation in 1933. Thirty-one of these installations protect 14 line sections covering approximately 750 miles of single-circuit line. The other three installations are a solution of a special case and provide protection primarily for simultaneous trouble occurring on both circuits of a short double-circuit line.

A tabulated summary of the operation of these carrier sets since their installation and the performance both on internal and external faults is given in table I. It will be noted that a total of 203 internal faults were experienced on these sets during the period 1933–1937, all of which were cleared correctly by the carrier relays. In other words, there was no case where relaying was called for that the relays did not perform to clear the faulted section of line. This the authors believe, is unusually successful performance. During the same period 27 incorrect carrier relay operations occurred on external faults—that is, there were 27 cases where faults occurring on sections external to those on which the carrier relaying was installed, resulted in action—incorrect action—within the sections on which carrier relaying was installed.

An analysis of these 27 incorrect actions is given below. It is worth noting, however, that some possible 2,000 external faults occurred during the same periods in all of which the carrier relaying operated correctly, that is, the carrier operated to block within the healthy section.

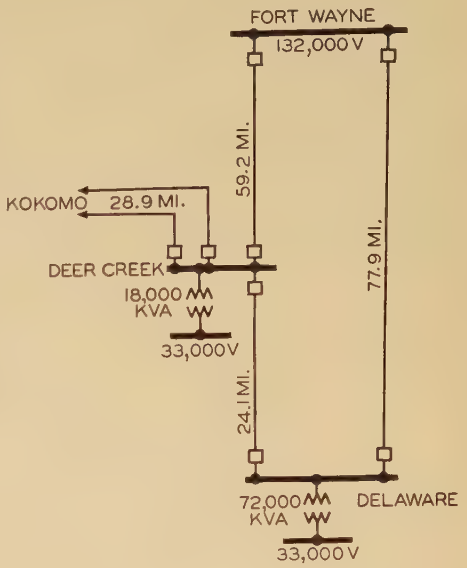

Figure 7. Illustrating problem 5: 132-kv system of Indiana & Michigan Electric Company radiating from Fort Wayne and supplying Deer Creek and Delaware stations of Indiana General Service Company

Another way of stating this is that proper blocking did not occur in some one per cent of the total cases carrier was called to block. The causes for failure to operate in this one per cent of the cases were the following:

(*a*). Seven of these operations were due to rain splashing up onto the protective gaps on the coupling capacitors from the under side thus shorting the gaps out for short periods of time and preventing the transmission and reception of carrier. This difficulty was corrected by increasing the gap settings and by providing better gap shielding.

(*b*). Two of the incorrect operations were due to vacuum gaps used in the trap units becoming defective. This caused the gaps to break down during fault conditions, preventing the transmission and reception of carrier. This difficulty was remedied by testing and checking vacuum gaps periodically once a year.

(*c*). Four of the operations were due to the tripping relay on the four-cycle carrier scheme not opening its contacts on resetting before the receiver relay had closed its contacts in the reset position. This trouble was eliminated by the installation of an instantaneous pickup time delay dropout lockout relay which gave sufficient time for the tripping relays to reset, preventing false operations.

(*d*). Four were due to the power directional relay contacts getting out of adjustment so the contacts did not close positively enough when they should have closed to transmit carrier. All of these four operations occurred on the same day and happened before the relay man reached the station to determine the cause of trouble. This trouble was remedied by adjusting the directional contacts so as to give plenty of wipe to insure positive closing of contacts.

(*e*). Eight of the operations were due to the adjustments of contacts on the fault detector and power directional relays changing with time. This was remedied by installation of more positive fault detector and power directional relays which so far have shown that they do not alter their adjustments with time.

(*f*). One of these operations was due to the tripping relay at one terminal being set through an error lower in magnitude than the starting relay at the other terminal. This obviously was bound to cause an incorrect operation on an external fault.[7] The remedy was simple.

(g). One of the operations was due to the voltage control relays employed with the four-cycle carrier scheme not being set properly at both terminals to take account of the difference in voltages at the two stations for a case of system instability. This condition has been remedied since then by employing proper settings on the undervoltage relays at the two terminals to take care of instability conditions.

It will be noticed in every case the definite cause for the failure to block properly was found and the necessary remedy determined. This should therefore eventually give perfect performance. That this is not an unreasonable expectation is evidenced by the record of only a single incorrect operation during 1937, the period when the maximum number of installations were in service.

IV. Maintenance Experience With Carrier Equipment

Those who have not had intimate experience with vacuum tube equipment have sometimes shied at the application of carrier because of the seemingly great complication of carrier circuits or the lack of sufficient confidence in the thorough reliability of carrier and vacuum-tube equipment in general. The experience running over some two decades with carrier and carrier tubes has been described elsewhere.[8,9] Subsequent to the time the above performance was described, further operating experience confirmed the utmost reliability of the carrier circuits and of the vacuum tubes and their concomitant equipment. Nevertheless it needs to be pointed out that reliability is not automatic and can be obtained only by a systematic, even though a comparatively simple, maintenance program. In this regard the experience on the system with which the authors are connected may be of interest. The program carried out here is as follows:

Table I. Summary of Carrier-Current Relay Operations on 34 Installations for Period of 1933–1937

Company	Line	Kv of Line	Length of Line (Miles)	Date Carrier Relaying Put in Service	Operations on Internal Faults 1933	1934	1935	1936	1937	Total	Incorrect Operations on External Faults 1933	1934	1935	1936	1937	Total
Appalachian Electric Power Company	#1 Cabin Creek-Turner	132	23.6	Aug. 3, 1934		0	2	4	0	6		0	0	7	0	7
	#2 Cabin Creek-Turner	132	23.6	Aug. 3, 1934		0	5	1	0	6		1	4	0	0	5
	#1 & #2 Cabin Creek-Turner	132	47.2	Aug. 3, 1934		0	0	3	1	4		0	0	0	0	0
	Roanoke-Fieldale	132	37.9	Apr. 5, 1935			3	7	6	16			3	1	0	4
Indiana & Michigan Electric Company	Fort Wayne-Deer Creek	132	59.2	May 18, 1936				4	5	9				1	0	1
	South Bend-Michigan City	132	41.1	Apr. 16, 1937					2	2					0	0
	South Bend-Plymouth-Michigan City	132	77.6	Apr. 16, 1937					3	3					0	0
	South Bend-Michigan City & South Bend-Plymouth-Michigan City	132	118.7	Apr. 16. 1937					1	1					0	0
The Ohio Power Company	#1 Philo-Howard	132	80.6	June 22, 1934		4	2	7	5	18		0	0	0	0	0
	#2 Philo-Howard	132	80 6	June 22, 1934		1	5	0	3	9		0	0	0	0	0
	#1 & #2 Philo-Howard	132	161.2	June 22, 1934		1	2	4	3	10		0	0	0	0	0
	#1 Howard-Fostoria-Lima	132	89.5	Aug. 4, 1933	3	16	0	1	1	21	0	0	0	0	0	0
	#2 Howard-Fostoria-Lima	132	89.5	Aug. 4, 1933	3	9	3	5	5	25	0	0	0	0	0	0
	#1 & #2 Howard-Fostoria-Lima	132	179.0	Aug. 4, 1933	0	0	0	0	0	0	0	0	0	0	0	0
	#1 Fort Wayne-Lima	132	63.2	June 5, 1933	3	4	4	2	6	19	1	1	0	0	0	2
	#2 Fort Wayne-Lima	132	63.2	June 5, 1933	2	8	2	4	2	18	0	1	0	0	1	2
	#1 & #2 Fort Wayne-Lima	132	126.4	June 5, 1933	1	1	1	1	0	4	1	0	0	0	0	1
	#1 & #2 Philo-Zanesville-Crooksville	132	43.9	June 21, 1934		0	0	0	0	0		0	0	0	0	0
The Scranton Electric Company	#1 Stanton-Suburban	66	10.85	June 9, 1934		3	2	2	0	7		2	1	0	0	3
	#2 Stanton-Suburban	66	10.85	June 9, 1934		2	8	5	4	19		2	0	0	0	2
	#1 & #2 Stanton Suburban	66	21.7	June 9, 1934		0	1	4	1	6		0	0	0	0	0
	Total				12	49	40	54	48	203	2	7	8	9	1	27

The transmission and reception of carrier are checked regularly by the station operators. At attended stations this check is made once each shift and at unattended stations it is made daily. This test is an over-all check of the carrier current operation and consists of each station transmitting in turn and reading the received signal from the distant station and the back-feed from the local transmitter, by means of a test plug and milliammeter provided for the purpose on the switchboard. Any abnormal variations in the readings obtained are reported immediately by phone and the trouble is located and corrected by the carrier current maintenance man.

More detailed tests and inspection of the carrier-current equipments are made regularly once every three months by the carrier current maintenance engineer. These detailed tests include checking the tubes, operating voltages and currents; checking the transmitter-receiver unit for proper frequency and output, margin of received signal available, and interference from other carrier channels; checking "*B*" batteries for output capacity; checking line trap units for proper operation, and a thorough visual inspection of all the equipment.

The following summarizes the troubles and experience with carrier current equipment over the past four and one-half years as determined from the routine tests.

1. VACUUM TUBES

Vacuum tubes have shown exceptionally long life and a high degree of reliability. Many of the type 210 tubes installed three to four years ago are still in service. The shortest life recorded on this type of tube was 3,600 hours and an average life of over three years is being obtained. In later equipments screen grid tubes were used for grid control of carrier transmission. Experience with the type 48 tube used in a few installations showed that it had insufficient insulation to withstand the lightning and switching surges which occur and a vacuum gap protector was added to the equipment to prevent the surge voltages from getting to the tubes. This corrected the trouble due to voltage breakdown of the tubes and an average life of approximately one year has since been obtained with these tubes. The latest sets use type 802 tubes and no failures have occurred during the six month service period to date.

2. “B” Batteries

At some stations heavy duty “B” batteries are used as plate supply for the transmitter and receiver tubes. These have a life of between one and two years in this service but are normally replaced once a year. In some cases where these batteries were not replaced yearly, the end of life was definitely indicated by the regular daily tests.

3. Trap Units

Line trap units developed the following faults:

(*a*). Paper condensers originally used varied their capacity with temperature, causing a change in tuning. This was corrected by using mica type condensers.

(*b*). It was found that the mica type condensers due to their low impulse strength broke down in several instances on lightning surges and protectors were added. In the one instance of trouble since the above change was made lightning destroyed the vacuum gap but did not harm the tuning condensers.

(*c*). Out of 37 traps in use there has been one case in which trap coils were deformed by a heavy fault current. This occurred on an internal line fault with an estimated short circuit current of 6,800 amperes and both line traps were affected.

4. Transmitter Receiver Units

Maintenance experience with the transmitter receiver units has been quite satisfactory after the few minor defects in early equipments were corrected. These included:

(*a*). The master oscillator was not sufficiently stable in frequency for satisfactory operation. This was corrected by redesigning the master oscillator circuit to provide more circulating energy in the oscillator tank and to reduce the coupling between the oscillator and power amplifier tubes.

(*b*). The air tuning condenser in the master oscillator circuit was originally connected between the tube plate and ground. It was found that any transient which broke this condenser down was followed by continuous arcing of the condenser fed from the d-c plate supply voltage. This trouble was corrected by using a fixed condenser in series with the variable condenser.

The relay circuit employed with carrier relaying is tested monthly to determine that the circuit breaker will trip from the carrier relays and in addition the blocking action for an external fault is checked. In the case of the one-cycle carrier system where more delicate adjustments of relays are necessary, their over-all adjustments are checked monthly by operating each fault detector relay manually with power flow into the bus and noting that the receiver relay contacts do not move and remain in the open position. Once every six months the relays are calibrated, inspected, and readjusted where necessary.

V. Conclusions

The authors believe as a result of their experience in developing and applying carrier current relaying, outlined in this paper that the following facts stand out particularly:

1. Carrier current relaying is definitely out of the experimental class and is now thoroughly practical, simple, reliable, and relatively low in cost.

2. This form of relaying is universal in its application.

3. Where conventional relay schemes have been applied up to their limit from the standpoint of getting proper selection, carrier relaying offers a solution for adding additional sectionalizing stations without disturbing the existing relay set-up or increasing sectionalizing time. At the same time, on the new protected sections sectionalizing time can be made a minimum.

4. Where a system is sensitive to fault initiated voltage disturbances, carrier relaying is the only practical form of protection which for every location and kind of fault will give short enough sectionalizing time to keep the duration of these voltage surges short enough.

5. The limit on loading of important tie lines without running into instability problems, is largely determined by the speed with which faults can be cleared. Carrier relay protection, which is the fastest practical universal scheme so far developed, materially aids in the operation of such tie lines to maximum advantage. Instability difficulties on short lines radiating from large generating stations can be effectively reduced by the application of this fast protection.

6. The development of ultrahigh-speed reclosing hinges directly on high-speed relaying both because total operating cycle time must be a minimum and because cascading of breakers cannot be tolerated. Carrier current relaying again is the only practical form of relay protection which will accomplish this.

7. The applications outlined above have been developed on the basis of experience. They have not been found difficult to carry out. It may be found possible to further simplify the present scheme with time, but even as it stands, it has been found to be comparatively simple. The equipment with which this work is being done has, on the other hand, during the period it has been in service proved to be most rugged. It has given quality and reliability of protection few dared to think possible only about a decade ago.

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The Rating of Resistance-Welding Transformers

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Synopsis: The present method of rating resistance-welding transformers varies with the different manufacturers, causing a certain amount of confusion among the users of this equipment. It is recommended that a standard method of rating, based on the thermally equivalent continuous output, be adopted and adhered to by the manufacturers. The general requirements of a welding transformer are discussed for the purpose of explaining the desirability of such a standard rating.

Certain of the recommendations made herein are already embodied in the present AIEE Standards for resistance welding apparatus, and in the standards adopted by the Resistance Welder Manufacturers Association, but it is further recommended that these standards be altered to require additional name plate data.

It is hoped that the transformer manufacturers and users will recognize the desirability of such standardization, and co-operate in its universal adoption.

FOR various reasons comparatively little technical information has been published concerning resistance welding, and today, only those who have had close contact and shop experience with this process are familiar with the problems involved, both as to the technique of welding as well as to the requirements of the equipment. It is the purpose of this paper to discuss one of the most important items of the equipment—the welding transformer—and offer further suggestions and recommendations as to the standardization of this part of the welding apparatus.

In the early days of resistance welding the transformer was considered not so much as a piece of electrical equipment but rather as incidental to the welding machine as a unit. The welding engineer himself knew comparatively little concerning the requirements of the transformer. He knew primarily that a relatively low voltage applied to a localized area of the pieces to be joined would cause a current to flow through these pieces, thus generating sufficient heat to fuse them together.

In stationary welding machines the transformer is connected to the welding electrodes through short conductors of rather large cross section. The secondary or load circuit is therefore of very low impedance, and the tendency is to consider it as effectively a short circuit on the transformer. This condition might be rather confusing to some engineers concerned with welding. How is it possible in the light of conventional transformer design knowledge, to design and build a transformer to stand up under the repeated short circuits demanded by the welding job? In fact I have heard it said by some that it was impossible to build a transformer which would stand up and that failures due to burn outs were to be expected. It is, I presume, partly because of this condition that welding transformers have the vagueness as to rating that they now have. It is fairly axiomatic in the welding profession that transformer ratings mean little if anything at all. I have found in the past that a transformer manufactured by "*A*" might be physically much larger than the unit of the same name-plate rating manufactured by "*B*," yet load tests and actual service have in certain instances, shown that the larger transformer may, under the same loading, fail before the smaller one. This condition is due primarily to the fact that although the name-plate kilovolt-ampere rating of the two transformers is the same, the method of determining this rating may vary considerably.

The welding manufacturers are aware of this condition and have taken certain steps toward standardization. Through mutual co-operation, under the sponsorship of the Resistance Welder Manufacturers Association, they have adopted transformer standards which call for a name-plate rating based on a 50 per cent duty cycle. In general, however, these standards pertain mostly to the method of manufacture, quality of materials, and limiting values of current and flux density to be used, and not so much to the over-all performance of the transformer.

Certain of these standards are desirable yet others, I feel, are superfluous. In order to allow the manufacturer latitude in his design he should not be limited, for example, as to the current density he uses. He should be allowed to increase the current density if he desires, thus reducing the weight of his unit, if he can at the same time provide sufficient cooling. On the other hand limitations as to flux density are desirable, as will be explained later. In general I feel that these particular standards do not necessarily insure uniformity as to performance, neither do they convey very definite information as to the capabilities of the transformer. A group of standards relating to performance is the logical way of relieving this condition.

The present AIEE Standard No. 39, pertaining to resistance welding apparatus require that the welding transformer rating shall be a continuous rating, the thermal effects of which shall be as nearly as possible those of the actual duty for which the transformer is intended. These standards pertain entirely to the performance of the unit. They furthermore require the following minimum name-plate data on each unit.

1. Manufacturers name, address, etc.
2. Input in kilovolt-amperes (continuous rating).
3. Frequency.
4. Primary current.
5. Primary voltage.

However, these standards do not entirely cover the subject. Also, my experience has been that comparatively

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1. For numbered reference, see end of paper.

few people active in the welding profession consider them very seriously. I therefore feel that some additional recommendations as to transformer standardization, based on the performance of the unit, are needed, and that a discussion might be helpful in bringing to the attention of manufacturer and user the reasons for these standards and the desirability of their universal adoption.

Before making recommendations, I should like first to discuss in general the requirement of a welding transformer in the hope that a better understanding of the operating conditions may be conveyed. This discussion will deal with the following:

1. Required current and voltage during the welding period.
2. Duty cycle.
3. Thermally equivalent continuous kilovolt-ampere rating.
4. Transformer impedance.
5. Flux density.
6. Secondary voltage range.
7. Transformer cooling.

The scope of this paper does not permit a discussion of the detail design features of the transformer.

Requirements of the Welding Transformer

In making a resistance weld, one requirement, among many, is a flow of electric current through the parts to be joined. It is the function of the welding transformer to supply this current. Its magnitude and the length of time during which it flows depends upon factors determined by the particular welding job and it is not the purpose of this article to discuss these factors. Let us start with the assumption that a certain current is required to flow for a certain length of time for each weld, and discuss the effect of these requirements upon the specification and rating of the transformer.

The function of the welding transformer being to supply current to the parts to be joined, implies that a certain voltage is necessary at the terminals of the transformer in order to force this current through the impedance of the circuit which conducts the current from the transformer to the welding electrodes. This impedance constitutes the load on the transformer and is composed of the resistance and reactance of the conductors and of the weld metal and joints. It is usually very low as compared with load impedances encountered in the average lighting or power application, yet it imposes a definite load on the transformer, and not a short circuit.

One of the first requirements of the welding transformer is therefore, that the magnitude of its secondary terminal voltage under load conditions shall be sufficient to force the required welding current through the impedance of the external welding circuit. This voltage will be equal to the numerical product of the circuit impedance in ohms, and the welding current in amperes, and in order to determine it we must of course know the numerical value of the load impedance. The size, spacing, and length of the conductors leading from transformer to welding electrode, determine this impedance, and these requirements are dictated by the practical requirements of the particular job to be welded. For example, if a large sheet is to be spot welded at its center by means of a stationary machine, the welding electrodes of the machine must be far enough away from the transformer to allow the edge of the sheet to clear it when the sheet is in the position for welding. This determines the length of the external circuit which is commonly referred to as the "throat depth" of the machine. If on the other hand the sheet has a vertical flange which must fit into the throat of the machine in order to place the sheet in position for welding, then the spacing of the conductors must be such as to clear this flange when in the welding position. This determines the "throat height" of the machine. Some commercial stationary machines are built with adjustable throat depth and height, thus presenting different load impedances depending on the particular adjustment being used.

In certain other applications, such as assembly operations where the welding machine must be carried to the work, the so-called portable welding equipment is employed. In such applications the welding tool is connected to the transformer by means of flexible copper conductors, the length, spacing, and size of which depend upon practical considerations. This in turn determines the impedance of the welding circuit, external to the transformer. In most instances the cables can be tied together throughout most of their length except at their ends where they must be separated in order to facilitate fastening to the transformer terminals and to the tool. This keeps the impedance to a minimum and prevents variations due to the cables swinging apart. In one such commercial applications these cables are five feet in length and the total external circuit impedance is about 0.001 ohm.

The load impedance required for any particular job can in most cases be calculated with sufficient accuracy. For practical purposes, however, if a sample set up can be conveniently made, the impedance can be measured by means of a voltmeter and ammeter.

One practical method of measuring this impedance is as follows. By means of any available transformer, force a certain current through the impedance. Then measure this current by means of an ammeter and current transformer and also measure the voltage across the impedance. The ohmic value of the impedance is then:

$$Z_{\text{load}} = E/I$$

Since the ratio of E to I will be constant for a given impedance, the numerical value of the current chosen will be immaterial in so far as the result is concerned. However if the impedance is exceptionally small a rather large current may be necessary in order to produce a voltage drop which can be read with any degree of accuracy with the average shop instrument. Under such conditions, a current transformer with ratio high enough to measure the current may not be available. In this case the turns ratio (A) may be determined by measuring the no-load primary and secondary voltage. Then with the load connected the primary current and load voltage are measured. The value of the load impedance is then:

$$Z_{\text{load}} = \frac{E_{\text{load}}}{A \times \text{primary current}}$$

Once this is determined, the numerical product of this impedance and the required welding current is equal to the voltage which must be maintained at the transformer terminals while it is delivering this current. In most practical welding applications this output is required for only a fractional part of a second to complete the weld. The power is then interrupted and the material progressed to the next weld location. For convenience I should like to refer to this product of root-mean-square current and volts during the welding period as the instantaneous kilovolt-ampere output of the transformer. The instantaneous kilovolt-ampere input will of course be somewhat higher due to the impedance voltage drop in the transformer.

Some manufacturers have in the past assigned kilovolt-ampere ratings to their transformers which they say is the maximum instantaneous kilovolt-ampere which it will demand from the line. In my opinion this rating means very little if anything in so far as the transformer itself is concerned.

Assuming a constant primary voltage, the instantaneous kilovolt-ampere input for a given ratio of transformation, will depend upon the load impedance, reaching a maximum when the load impedance is practically zero, under short circuit conditions. The internal impedance of the transformer will therefore establish the maximum instantaneous kilovolt-ampere that it can demand from the power supply. A rating stated in this manner is therefore nothing more than a statement of the internal impedance of the transformer. In cases where the transformer forms a part of the complete welding machine, the minimum load impedance is fixed by the minimum throat depth and height, and this impedance together with the internal impedance of the transformer will limit the maximum instantaneous kilovolt-ampere input. It is then perfectly legitimate to assign such a rating to the machine as a whole, but such a rating would mean very little if applied to the transformer alone. This rating when assigned to the machine informs the user as to the maximum instantaneous kilovolt-ampere that his lines and other power equipment must be capable of supplying, but it does not give him the complete story. It does not, for example, tell him whether the transformer is capable of performing a certain welding operation without burning out. This answer cannot as yet be given because we do not have sufficient information concerning the requirements of the transformer.

Duty Cycle

We have already assumed that in making a resistance weld, a certain current is required to flow for a definite length of time. This current flowing through the windings of the transformer will generate heat in the windings, which is proportional to the square of the current and to the length of time during which it flows. The average heating effect will therefore depend upon the time length of the current flow required to make one weld and upon the average number of welds per minute required of the machine. It follows therefore that a transformer which makes 20 ten-cycle welds per minute will develop twice as much heat in its windings as a transformer making only ten ten-cycle welds at the same current. As a result it must dissipate twice as much heat in the same length of time if the temperature of its insulation is to be kept below the danger point. It must therefore be designed accordingly, and although the two transformers deliver the same instantaneous output they must be quite different in design and construction.

The ability of any transformer to perform satisfactorily without overheating, depends upon its ability to dissipate the heat generated internally. If its thermal characteristics are such that it cannot dissipate this heat without exceeding the safe operating temperature of its insulation, the transformer will soon fail.

This immediately establishes another requirement of a satisfactory welding transformer, namely, that it shall have sufficient heat dissipating capacity to prevent overheating when delivering the required instantaneous kilovolt-ampere output, at a specified welding time and frequency of operation. The number of conducting cycles per weld, and the number of welds per minute establish the fractional part of a minute during which the transformer supplies current. This fraction is commonly referred to as the duty cycle of the transformer, and must be known by the designer in order that he may incorporate the above requirement into his design.

Thermally Equivalent Continuous Kilovolt-Amperes

A transformer fulfilling these two requirements as to secondary voltage and heat dissipating ability, will perform satisfactorily on any welding operation so long as the specified loading is not exceeded. The requirements so far have been specified with no reference whatever to kilovolt-ampere capacity. We have merely stated that the transformer shall be capable of delivering a specified secondary current at a specified duty cycle and maintaining under load conditions a specified voltage across its secondary terminals. There is no more simple way of stating the requirements, yet, it is desirable for various reasons to assign a kilovolt-ampere rating to the transformer. How then, from the information so far given, can we assign a logical and legitimate rating?

In all power and distribution transformers the kilovolt-ampere rating of each unit is equal to the kilovolt-ampere that it can deliver continuously without overheating, when operated under specified cooling conditions. Then why not, for the purpose of standardization, rate welding transformers accordingly? Some may say that this is not legitimate because the welding transformer is never called upon to operate continuously. The same may be said about power and distribution transformers, because during certain hours of the day they may operate under a considerable overload, while during the remaining hours they are very much underloaded. Yet they perform satisfactorily so long as the heating in the transformer, averaged over a period of time dependent upon the size and design, does not exceed the heating which would be caused if the transformer operated continuously at its rated kilovolt-amperes.

Since the heating effect of the current is proportional to the square of the current, it follows that a certain current flowing for 25 per cent of the time will produce the same average heating as a current of one-half that value flowing continuously. Therefore from a heating standpoint, this continuous current is thermally equivalent to the instantaneous current multiplied by the square root of the duty cycle. This, I should like to call the thermally equivalent continuous current, which multiplied by the secondary load voltage becomes the thermally equivalent continuous kilovolt-ampere output of the transformer. This we may call the kilovolt-ampere output capacity of the transformer, but since in the case of power and distribution transformers the rating is determined by the product of load current and open circuit secondary volts, I recommend that the same method be employed in rating welding transformers.

Impedance

In discussing the welding transformer, my remarks have so far been confined to the secondary load voltage. To determine the open circuit secondary voltage we must know the impedance of the transformer. In other types of transformers this is usually expressed as impedance voltage drop in per cent of open-circuit secondary volts, at a specified loading which is usually the thermally equivalent continuous kilovolt-ampere rating of the transformer. It is my further recommendation that the same custom be adopted for welding transformers. However, since the instantaneous kilovolt-ampere output of the welding transformer will be equal to its thermally equivalent continuous output divided by the square root of the duty cycle, then the per cent impedance voltage drop in the transformer at its instantaneous output will be equal to the per cent impedance drop at the equivalent continuous output divided by the square root of the duty cycle.

Therefore the impedance voltage drop in the transformer during the welding period will be

$$Z/\sqrt{D}$$

where

Z = per cent impedance voltage drop at the thermally equivalent continuous output
D = duty cycle

The open-circuit voltage of the transformer will then be the vector sum of the load voltage and the internal impedance drop. The phase angle of these two voltages will vary, depending on the phase angles of the transformer impedance and of the external welding circuit. Their vector sum will therefore reach a maximum when both phase angles are the same. In other words, if we assume a certain required secondary load voltage, the required open circuit secondary voltage will be a maximum when the load voltage and the transformer impedance drop are exactly in phase. I therefore recommend that, in calculating the required open circuit secondary voltages or in specifying the transformer impedance voltage drop, these two voltages be assumed to be in phase.

Some users may be concerned with the magnitude of the internal impedance of the transformer at continuous rating. If this is high, a higher open-circuit voltage will be necessary in order to maintain a given secondary load voltage. This means a lower ratio of transformation and hence a larger primary current. In most cases this means very little, in so far as power consumption is concerned, but in any case it causes more heating and more voltage drop in the primary line feeding the transformer. On the other hand if the specified impedance is too low the additional transformer cost may not be justified. This impedance should therefore be specified so as to strike an economic balance between the two extreme conditions. After consulting various manufacturers and experimenting with various designs, it appears now that the most economical impedance is from 4 per cent to 6 per cent. I, therefore, recommend that a transformer impedance of 6 per cent be adopted as standard unless otherwise specified.

It is usually not considered good practice to design or specify a transformer to operate at an instantaneous output of more than about three times the thermally equivalent continuous output. If the required instantaneous output is higher than this, the instantaneous impedance voltage drop in the transformer becomes excessive, and it is advisable to employ a transformer with a higher continuous rating. This means that although the actual welding duty cycle may be only 1 per cent on a certain job, the duty cycle used in calculating the thermally equivalent continuous output should be not less than 9 per cent. As an illustration let us assume the following conditions as determined by the welding job.

Required secondary current during weld = 10,000 amperes
Welding circuit impedance = 0.001 ohms
Length of current flow per weld = 7 cycles
Number of welds per minute = 10

From this we see that the number of conducting cycles per minute is 7 × 10 = 70 and the actual duty cycle 70/3600 = 0.0195 or 1.95 per cent. Also that the required load voltage is 10,000 × 0.001 = 10 volts. If then we assume a transformer impedance of 4 per cent at its continuous rating, its impedance voltage drop during the weld will be:

$$Z/\sqrt{D} = \frac{0.04}{\sqrt{0.0195}} = \frac{0.04}{0.14} = 0.285$$

or 28.5 per cent.

The required open-circuit secondary voltage will then be 10/(1–0.285) = 14 volts.

The thermally equivalent continuous kilovolt-ampere output will be

$$\frac{10{,}000 \times 14 \times \sqrt{0.0195}}{1{,}000} = 19.6 \text{ kva}$$

but due to the fact that the transformer loading during the welding period is (10,000 × 14)/1,000 = 140 kilovolt-amperes or 7.15 times the continuous rating, the instantaneous impedance drop in the transformer is 7.15 × 4 per cent = 28.5 per cent.

Assuming a 220-volt primary the instantaneous flow of current from the line (neglecting exiciting current) will be

$$\frac{14}{220} \times 10{,}000 = 638 \text{ amperes}$$

If, on the other hand, we use a duty cycle of nine per cent in calculating the thermally equivalent continuous output, the instantaneous impedance voltage drop in the transformer will be

$$\frac{0.04}{\sqrt{0.09}} = \frac{0.04}{0.3} = 0.133 \text{ or } 13.3 \text{ per cent}$$

The open circuit secondary voltage will be 10/(1–0.133) = 11.6 volts and the instantaneous flow of current from the line will be

$$\frac{11.6 \times 10{,}000}{220} = 525 \text{ amperes}$$

The thermally equivalent continuous kilovolt-ampere rating of the transformer will in this case be

$$\frac{10{,}000 \times 11.6 \times \sqrt{0.09}}{1{,}000} = 34.7 \text{ kva}$$

This rating is almost twice that required from a thermal standpoint, yet from a standpoint of voltage regulation and primary current flow, this larger rating is usually justified.

Flux Density

It is desirable to limit the maximum flux density in a welding transformer in order to limit the transient exciting current during starting. In energizing any transformer, unless the circuit is closed at the proper point with respect to the voltage wave, the exciting current will contain a transient component which may be many times the normal exciting current.[1] The magnitude of this transient component will depend upon the point of closure of the circuit with respect to the voltage wave, and upon the normal flux density in the core. In normal welding service the transformer is started, or energized, many times per minute, and since many of the commercial welding transformer controls do not provide for repetitively closing the circuit at the proper point, rather high transient exciting currents might result, unless the maximum flux density is kept within reason. The existence of these high transient currents, places an additional burden upon the control apparatus and also produces additional heating in the primary of the welding transformer. With this type of control therefore it is desirable to limit the maximum flux density. The limiting value will depend upon the characteristics of the iron used in the core. The maximum flux density should be kept below the knee of the saturation curve. For the usual commercial transformer iron, I have found that a maximum flux density of 90,000 lines per square inch gives satisfactory operation but should not be exceeded. I believe that most manufacturers are conforming to this limit at the present time.

It might further be said that the full electronic type of control usually has provision for repetitively closing the circuit at the proper point to eliminate transients irrespective of the value of the flux density.

In such cases it is not so important to limit the flux density, except as it may be desirable to limit the normal exciting current. I feel, however, that irrespective of the type of control anticipated the maximum flux density, at maximum secondary voltage, should be limited so as to keep it below the knee of the saturation curve of the particular iron being used.

Secondary-Voltage Range

In practically all resistance-welding applications, it is desirable for various reasons, to provide some means of varying or adjusting the welding current. For a given welding condition, the external circuit impedance will be substantially constant. The only means therefore of varying the secondary or welding current is to vary the secondary voltage of the transformer. This can be accomplished either by varying the primary voltage impressed on the transformer or, by varying, the number of primary turns in the transformer. Since the first method requires a separate voltage-adjusting transformer in addition to the welding transformer, this is, in a number of instances, uneconomical. The most commonly used method of obtaining this welding current variation is to provide the welding transformer with a tapped primary winding. The previous discussion has dealt entirely with the maximum secondary voltage at which the rating of the transformer should be taken. Since the maximum secondary voltage occurs with minimum primary turns, in order to provide a lower secondary voltage a greater number of primary turns must be provided. For example if a maximum secondary voltage of 10 volts is obtained when using 22 primary turns, in order to obtain a minimum of 5 secondary volts with the same transformer, 44 primary turns must be provided. Since these additional primary turns take up space and add weight to the transformer, it is therefore desirable to specify the minimum as well as the maximum secondary voltage, so as to limit the number of primary turns. In order to insure uniform adjustment of voltage in between these maximum and minimum values it is furthermore desirable to specify the number of voltage adjustments available. For the average portable welding application, I have found that eight voltage steps ranging from 50 per cent to 100 per cent secondary voltage gives satisfactory operation. Applications may vary widely however, so that I do not recommend this as standard. I do recommend that the standards require the manufacturer to give this information, whatever it may be, on the name plate of the transformer.

Cooling

The above requirements can be met with an air-cooled transformer, however, this is considered uneconomical, particularly on the larger sizes. Most of the shops which use welding equipment are equipped with running water, and by using this water internally to cool the secondary winding of the transformer, the size, weight, and cost can be considerably reduced. In order to know the amount of cooling he can depend on from this source, the manufacturer must know or assume values for:

1. The temperature of the intake water.
2. The pressure available to force the water through the winding.

It must of course be remembered that the part of the internal heating attributable to core losses is directly proportional to the duty cycle, and that when tested at its continuous rating the transformer will develop slightly more internal heat than when operating at its equivalent intermittent capacity. This difference however is rather small due to the present tendency in design to make the core loss low and the copper loss high. This is done because most of the cooling is derived from the circulating water in the secondary winding and therefore the heat generated here can be dissipated more readily. In a typical design the ratio of copper loss to core loss was 4.5 to one measured at the continuous rating of the transformer. This gives a total loss of 5.5. The intermittent rating was at 50 per cent duty cycle so that under this condition the total loss would be 4.5 plus 0.5 or about 91 per cent of the total losses which would occur at the continuous rating. This allows a five per cent permissible increase in intermittent loading over the specified value, which gives a desirable safety factor.

Recommendations

In the foregoing, I have attempted to outline the electrical requirements of a welding transformer, placing them on a sound and logical basis. I have also attempted to outline my ideas and recommendations as to a logical basis of rating for such transformers. If the transformer is to give satisfactory and uninterrupted service, its thermal capacity must certainly be adequate for the particular job.

Due to ever-changing manufacturing methods, the user constantly finds it necessary to shift his welding transformers from one job to another or from one machine frame to another. He must therefore have knowledge of the capabilities of each of his units in order intelligently to apply them to his jobs, with assurance that they will perform satisfactorily, without overheating. This knowledge can be conveyed only when the transformer name plate bears the following information:

1. Manufacturer's name and address.
2. Rated primary voltage.
3. Frequency.
4. Open-circuit secondary-voltage range.
5. Thermally equivalent continuous kilovolt-ampere capacity (at maximum secondary voltage).
6. Per cent impedance at rated kilovolt-amperes (6 per cent unless otherwise requested).
7. Temperature rise.
8. Type of cooling required (if water cooled, state required gallons per minute at specified intake temperature).

It is therefore recommended that such name-plate data be considered for adoption as standard on all welding transformers whether they be individual units or part of a complete welding machine. In the latter case it is desirable that the maximum instantaneous kilovolt-ampere demand, or the maximum primary and secondary current of the machine as a whole be stated, in addition to the above data pertaining to the transformer.

With this data available the user, knowing the requirements of his job, does not need to go through the painful and expensive experience of a transformer failure to discover that it is too small for the job. Such experiences can be entirely eliminated to the decided benefit of user and manufacturer as well.

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Protection Features for the Joint Use of Wood Poles

Carrying Communication Circuits and Power-Distribution Circuits Above 5,000 Volts

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Synopsis: The paper reviews the historical development of joint use and the general results to date of studies of protective problems of lower and higher voltage joint use. The safety features are reviewed from the standpoint of (1) subscribers' premises, (2) employees, and (3) telephone plant. Characteristics of equipment of power and telephone plant as far as they relate to this problem are given. The various factors which determine magnitude and duration of the current and voltage in the telephone plant resulting from a contact with power conductors are discussed. Improved methods for obtaining safety under various conditions, where higher voltage joint use is found to be the best over-all solution, are described.

IN THE EARLY days it was the opinion of both the power and telephone industries that their respective lines should be kept apart except at unavoidable crossings. As the plants grew, this became more difficult and much overbuilding, conflicting construction, and some joint use resulted. By 1906 it was recognized that properly engineered joint use was generally preferable to overbuilding one line with another. Also, even at this early date it was recognized that, from the public point of view, joint use was more desirable than the construction of paralleling pole lines on the same street. However, no generally recognized construction specifications providing for adequate clearances, strength of construction, and suitable material were available and each situation had to be studied individually.

The first general joint use agreement was negotiated between a power company and a telephone company about 1906. This included joint use construction specifications worked out by the companies concerned. This formed the basis for many other subsequent agreements. Joint use construction methods have been under development ever since that time and the successful use during the last 25 years of joint poles for power circuits and telephone circuits has shown that such lines when constructed and maintained in accordance with recognized practices are the best engineering solution in many situations. There are today over 5,000,000 such joint poles in this country.

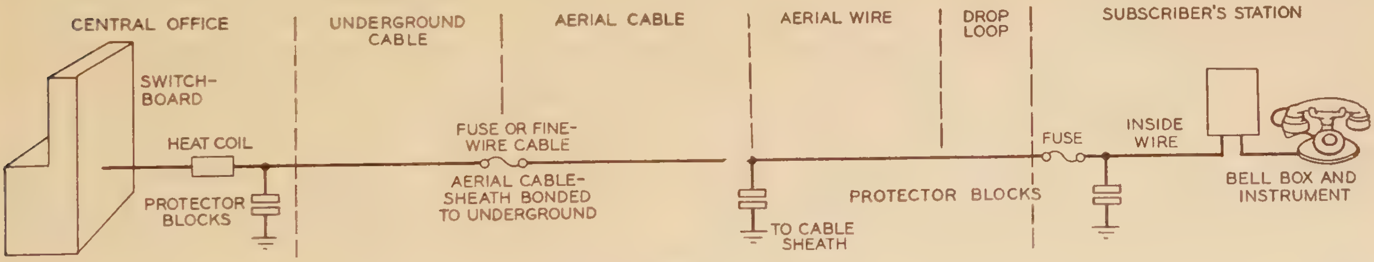

Figure 1

In 1926 the joint general committee of the National Electric Light Association and the Bell Telephone System recommended that the following general principles be adhered to as a guide in establishing joint use arrangements:

"Each party should:

a. Be the judge of the quality and requirements of its own service, including the character and design of its own facilities.

b. Provide and maintain facilities adequate to meet the service requirements including such future modifications in these facilities as changing conditions indicate to be necessary and proper.

c. Determine the character of its own circuits and structures to be placed or continued in joint use, and determine the character of the circuits and structures of others with which it will enter into or continue in joint use.

d. Co-operate with the other party so that in carrying out the foregoing duties, proper consideration will be given to the mutual problems which may arise and so that the parties can jointly determine the best engineering solution in situations where the facilities of both are involved."

In the earlier agreements for general joint use, a limitation of 5,000 volts was placed on the power circuits. This limit did not prove to be, in general, unduly restrictive in the earlier days, as distribution circuits were largely below this voltage and transmission circuits were above it. However, the engineers who made the studies upon which the early agreements were based recognized that there would be need for joint use above 5,000 volts in certain specific situations and that joint studies should be made with a view to providing standards for such cases. Shortly thereafter, specifications were adopted which provided for "higher grades" of construction for joint use involving the

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higher voltage circuits and for many years in specific situations where joint use could not practicably be avoided, such construction was adopted.

Later on, however, there was a marked increase in the use of higher voltage distribution circuits to meet growing loads and expanding service areas, and in recent years there have been an ever increasing number of instances where it has been necessary to consider general joint use in specific areas with voltages up to about 13 kv. In view of this, the joint subcommittee on development and research of the Edison Electric Institute and the Bell system undertook to find a less burdensome and more satisfactory solution to this problem. This paper outlines the progress, to date, which has been made in this connection.

Their study has included a detailed investigation of many of the factors in both the power and telephone systems which affect safety in the event of accidental contacts. Co-ordinative measures have now been developed which, where applicable, will provide safety for joint use with the higher voltages comparable to that enjoyed with joint use with the ordinary distribution voltages. In fact, it has been established that the degree of hazard in any proposed situation cannot be measured solely by the voltage of the power system and that numerous other factors must be taken into account.

Separate Lines Versus Joint Lines

Power transmission lines and telephone toll lines are of such a nature and so located that in general it has not been desirable to have them joint, and it has been generally feasible to find separate nonconflicting routes for such lines.

On the other hand, distribution circuits of both plants in urban and suburban and other built-up areas present an entirely different problem. In order to render power and telephone service to the individual customers, it is necessary to make provision for service connections of each utility to all houses on both sides of the street. In such a situation, if the power line were constructed on one side of the street and the telephone line on the other side, there would be frequent crossings of service connections under each line and criss-crossing of the services themselves. The construction and maintenance of such lines to provide for proper clearances involve many difficulties. With general joint use, telephone drop wires and power service wires both run from the same pole, simplifying the maintenance of proper clearances. At crossings, the probability of contact, in case of line wire failure, is materially less if the crossing occurs at a common pole rather than in mid-span. In view of these considerations, joint distribution lines are in general use in urban areas.

In rural or thinly settled areas the conditions are, of course, substantially different and it has been generally practicable and desirable to construct separate lines.

Telephone Circuits

Figure 1 shows a schematic layout of a Bell system local telephone circuit such as might be involved in joint use. Telephone plant between the central office and the subscriber includes underground cable, aerial cable, and aerial wire, any one or two of which, of course, may be absent in particular cases.

Table I. Causes of Contacts Between Power-Supply Conductors and the Telephone Plant

	250 Volt-5 Kv	5-15 Kv
Conductor Failure	1,545	224
Pole Failure	96	54
Other Causes	355	85
Total	1,996	360
Conductor Failure	1,545	224
Cause Unknown	391	75
Storm	214	9
Trees	481	34
Lightning	41	28
Acts of Public	99	34
Glaze, Wind, Cold	189	15
Conductor Hits	93	10
Fires Near Line	11	
Defects	9	4
Insulator Failure	...	9
Splices	...	2
Miscellaneous	17	4
Pole Failure	96	54
Cause unknown	20	3
Storm	10	4
Acts of Public	23	17
Wind	15	14
Rotten	13	4
Falling Trees	4	
Fires Near Line	4	2
Electrical Burns	3	4
Guy Failure	3	4
Lightning	1	
Pole Inadeq. Reinf.	...	1
Soft Ground	...	1
Other Causes	355	85
Increased Sag	133	38
Trees	42	7
Constr. & Maint.	125	16
Indirect	39	6
Miscellaneous	16	18

Exposed telephone lines entering subscribers' premises are protected by a fuse in series with each line conductor and protector blocks which provide a spark gap between each line conductor and ground. When an overvoltage occurs, the protector blocks operate and ground the circuit. The value of the voltage on the subscriber's station wiring after operation of the protector blocks depends upon the impedance of the ground and the amount of fault current through it. The operation of the telephone fuse will remove this voltage from the telephone wiring and equipment on the subscriber's premises on the instrument side of the protector. Exposed local telephone lines entering central offices are equipped with protector blocks and fuses or a section of small gauge cable to act in place of the fuses. Exposed interoffice trunks and toll circuits are similarly protected.

Power Circuits

Figure 2 shows the elements of a power distribution circuit between the substation bus and the consumers' premises. In this diagram are included such elements as a reactor, voltage regulator, and residual current relay which might or might not be employed in specific cases. For these circuits a ground is provided on the wiring which is extended into the customers' premises in order to prevent a rise in potential of the interior wiring in case of contacts between primary and secondary or breakdown of the service transformer. This ground also drains off any static potential on these wires. In case of failure the operation of the transformer fuse or the substation circuit breaker interrupts the primary voltage. In certain cases branch circuit fuses are also included so that the whole primary circuit is not interrupted in case of a fault.

Factors Affecting Safety

In addition to the generally recognized construction features and protection practices, safety in joint use is largely affected by the four following factors:

1. Frequency of occurrence of accidental contacts between power and telephone circuits.
2. Voltage on the telephone plant when contact occurs.
3. Duration of excessive voltage on the telephone plant.
4. Current in the telephone plant when contact occurs.

Safety is a relative condition, there being no such thing, of course, as absolute safety. However, the highest degree of safety reasonably obtainable under the circumstances should, of course, be provided. In the studies upon which this paper is based, judgment from the safety standpoint was based on long experience with joint use with lower voltage distribution circuits.

Frequency of Occurrence of Contacts

Over the past 15 years Bell Telephone System companies have been collecting information on accidental contacts and their causes, the data being reasonably complete for the past seven years. These data consist mostly of cases involving joint use for the lower voltages and crossings for the higher voltages. The available data were analyzed and a summary of the analysis is given in table I.

This tabulation shows that for both voltage classifications a large majority of the failures resulting in contacts were caused by factors independent of the circuit voltage, such as storms, falling trees or branches, acts of the public, etc.

This study, combined with observations made during field inspections and general studies of causes of line failure, indicates, assuming proper construction and maintenance for the various voltages involved, that the frequency of occurrences of contacts will not be materially different at the higher distribution voltages from that experienced at the lower voltages.

Type of Plant

For joint construction following recognized practices, the probability of contact varies with the types of plant involved as indicated by the following:

1. Power circuits and telephone circuits, both of aerial wire construction. A failure of a power conductor will generally result in contact with one or more of the telephone conductors.
2. Aerial wire power circuits and lead-sheathed telephone cable. The probability of contact due to a power conductor failure is less than in (1) above.
3. Aerial wire power circuits and one or more telephone paired wires attached directly to the pole. Here the probability of contacts is less than (2) above, due to the protection afforded by the paired wire insulation.
4. Power conductors in cable. Regardless of the type of telephone plant, the probability of a fault which would result in a contact with the telephone plant is remote.

The type of plant also has an important bearing on the effects when a contact does occur as is discussed later, and should be given due consideration in any study of the safety of joint use situations. This is particularly important in situations of limited extent where the application of general co-ordinated measures would not be justified, as for example, where a few spans of paired wire are carried on power poles used for the higher voltage distribution circuits.

Trees

The presence of trees along streets may have a material effect upon the frequency of occurrence of contacts. If trees grow into the line, arcing may occur between the trees and the wires, weakening the wire and causing failure. To obtain satisfactory operation, higher voltage circuits generally require more definite clearance from trees.

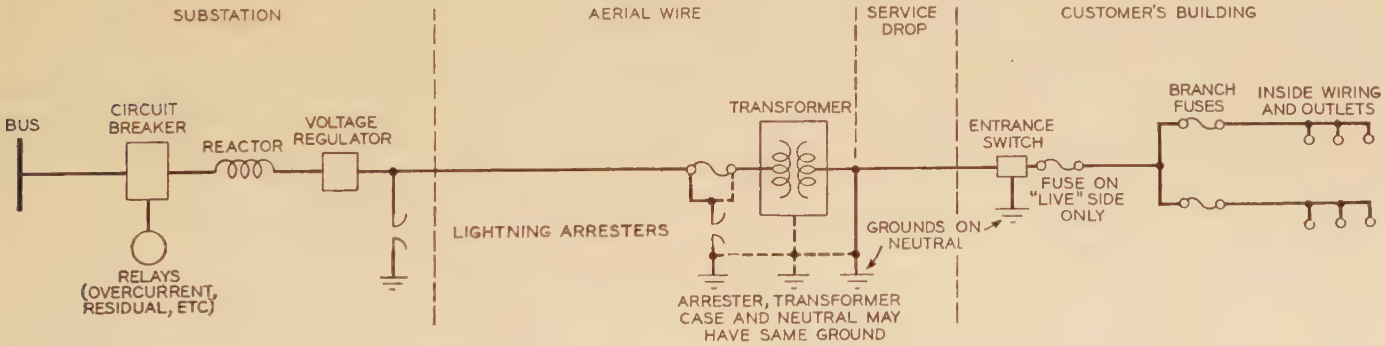


Figure 2

The effect of the trees can be overcome to some extent by the use of tree wire where the lower-voltage primaries are involved, but such wire has not been extensively used for the higher voltages. Where the power circuits are located above the trees, the branches afford some protection to telephone plant below them and in addition the

Table II. The Effects of Various Elements of the Circuit Involved in a Contact With the Telephone Plant

		4-Kv Wye	4.6-Kv Delta*	6.6-Kv Wye	6.6-Kv Delta*	13.2-Kv Wye	13.2-Kv Delta*
Kva of Substation and Power System Voltage. In general the substation may be represented by an impedance in series between the line and the power source which increases as the square of the voltage and decreases inversely as the kva. To illustrate the effect of substation kva and power-system voltage, a contact between the power circuit at a point one mile from the substation and a 1.5-inch diameter telephone cable grounded four miles away is assumed. The tabulation shows the contact voltage and current for a 200-kva and a 5,000-kva substation.	200 kva	I = 170	I = 220	I = 181	I = 195	I = 127	I = 118
		V = 1,340	V = 1,730	V = 1,420	V = 1,530	V = 1,000	V = 928
	5,000 kva	I = 235	I = 460	I = 381	I = 632	I = 675	I = 1,012
		V = 1,860	V = 3,620	V = 3,000	V = 4,960	V = 5,300	V = 7,950
Length of Power Line. The greater the length of power circuit between the substation and the point of contact, the smaller will be the voltage impressed on the telephone plant and also the smaller will be the currents in the fault circuit. To illustrate this, a power circuit three miles and 15 miles long, respectively, is assumed in contact with a telephone aerial cable of 1.5-inch diameter which is four miles from an underground section. This situation would result in voltages and currents as shown.	3 miles	I = 175	I = 348	I = 288	I = 500	I = 577	I = 1,000
		V = 1,380	V = 2,740	V = 2,280	V = 3,940	V = 4,550	V = 7,860
	15 miles	I = 67	I = 132	I = 110	I = 190	I = 219	I = 380
		V = 525	V = 1,044	V = 865	V = 1,500	V = 1,730	V = 3,000
Length of Aerial Cable in a Cable Contact. A 5,000 kva substation and five miles of power conductor is assumed in contact with an aerial cable of length one-quarter mile and four miles, respectively, the cable being one inch in diameter.	1/4-mile cable	I = 241	I = 474	I = 383	I = 635	I = 681	I = 1,010
		V = 137	V = 270	V = 220	V = 362	V = 388	V = 575
	4-mile cable	I = 135	I = 266	I = 219	I = 370	I = 410	I = 650
		V = 1,210	V = 2,400	V = 1,970	V = 3,340	V = 3,700	V = 5,850
Open-Wire Contact. To illustrate the effect of contact with open-wire circuit, assume a contact in middle of a four-mile telephone open wire run (0.109 iron), one station at end. Also assume a 5,000-kva substation and five miles of number 2 power conductor. Resistance of station ground and impedance of cable sheath assumed negligible.	Current at contact	I = 40	I = 80	I = 66	I = 114	I = 131	I = 225
	Voltage at contact	V = 1,990	V = 3,980	V = 3,280	V = 5,690	V = 6,550	V = 11,250
	Fuse duty	V = 2,160	V = 4,280	V = 3,540	V = 6,150	V = 7,090	V = 12,220
	Current through subscriber's fuse	I = 20	I = 40	I = 33	I = 57	I = 66	I = 113
Open-Wire Contact. Same as above except telephone wire parted and power conductor remaining in contact with subscriber end.	Current at contact	I = 22	I = 43	I = 35	I = 62	I = 71	I = 122
	Voltage at contact	V = 2,160	V = 4,280	V = 3,540	V = 6,150	V = 7,090	V = 12,220
	Subscriber fuse duty	V = 2,310	V = 4,600	V = 3,810	V = 6,600	V = 7,620	V = 13,200

* For delta circuits a double fault is assumed, one fault being located at the substation.

probability of faults resulting from broken branches, falling trees, etc., is reduced.

Voltage on Telephone Plant

The voltage on the telephone plant in case of contact is dependent upon the power circuit voltage and the ratio of the impedance in the telephone plant between the point of contact and ground to the total impedance of the fault circuit. Table II shows how the power circuit voltage, the substation capacity, the length and character of the power circuit, and the length and character of the telephone circuit affect the currents and voltages in case of contact.

In the subscriber plant the voltage at the point of contact is of prime importance, as a subscriber may be connected to the line nearby. On the other hand, for a toll circuit the voltage at the point of contact is of less importance and the voltage at the cable terminals or the terminals of the circuit should be used as a guide in connection with an appraisal of the situation.

Where the voltage on the telephone plant is higher than the capacity of the telephone fuse, the fuse may fail to clear the circuit and an arc be maintained across the fuse. Such an arc, if continued, may do considerable damage or start a fire. If the telephone fuse operates and opens the circuit the potential will remain on the drop wire. If this potential is above the dielectric strength between the conductors of the drop wire, failure of the insulation may also result.

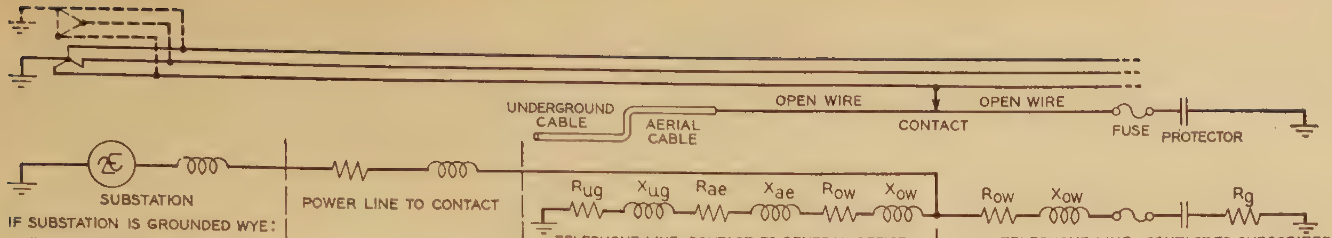
POWER-SYSTEM IMPEDANCE

The major elements involved in the power-system impedance are the substation and the power line up to the point of contact. The line impedance is dependent mainly on the length of the line and the wire size, as indicated in table *C* of figure 3. Line impedance is independent of the circuit voltage. The substation transformer may be considered as an impedance in series with the line. Transformer impedance (assuming the same percentage reactance) varies directly with the square of the voltage and inversely with the kilovolt-amperes. Values for various line voltages and station capacities are given in table *A* on figure 3. Since for the delta connection a double fault is involved, the equivalent substation impedance is twice the value for the wye connection, assuming the same capacity and line voltage. For single-phase circuits the correct transformer reactance is given in table *A*, if single-phase voltage and transformer capacity are used.

TELEPHONE SYSTEM IMPEDANCE

For a given power circuit condition, the voltage impressed upon the telephone plant is dependent upon the telephone circuit impedance from the point of contact to ground.

Contacts with telephone cable result as a rule in lower voltages on the telephone plant than do contacts with open wire, because cable sheaths usually present a lower impedance to ground. When a contact with a telephone cable occurs, the impedance to ground of the telephone plant is the impedance of the aerial cable sheath between



SUBSTATION

IF SUBSTATION IS GROUNDED WYE:
E = VOLTAGE FROM LINE TO NEUTRAL
SUBSTATION REACTANCE $= X_t$ FROM TABLE A
IF STATION IS ISOLATED DELTA:
E = VOLTAGE FROM LINE TO LINE
X_t = 2 TIMES VALUE SHOWN IN TABLE A
NOTE:— FOR DELTA CIRCUITS A DOUBLE FAULT IS ASSUMED

POWER LINE TO CONTACT

POWER LINE IMPEDANCE $= (R_L + jX_L)$ FROM TABLE C

TELEPHONE LINE. CONTACT TO CENTRAL OFFICE
TELEPHONE PLANT IMPEDANCE
$= [R_{ow}$ (TABLE B) $+ R_{ae}$ (TABLE D) $+ R_{ug}$ (TABLE E)$]$
$+ j[X_{ow}$ (TABLE B) $+ X_{ae}$ (TABLE D) $+ X_{ug}$ (TABLE E)$]$
$= (R_{co} + jX_{co})$
$= \overline{Z}_{co}\underline{/\theta_{co}}$ MAGNITUDE AND ANGLE FROM CHART

TELEPHONE LINE. CONTACT TO SUBSCRIBER
TELEPHONE PLANT IMPEDANCE
$= [R_{ow}$ (TABLE B) $+ R_g$ (TABLE E)$]$
$+ jX_{ow}$ (TABLE B)
$= (R_{sub} + jX_{sub})$
$= \overline{Z}_{sub}\underline{/\theta_{sub}}$ MAGNITUDE AND ANGLE FROM CHART

IMPEDANCE OF THE 2 PATHS TO GROUND IN THE TELEPHONE PLANT

SERIES $= (R_{co} + R_{sub}) + j(X_{co} + X_{sub}) = (R_{ser} + jX_{ser}) = \overline{Z}_{ser}\underline{/\theta_{ser}}$ MAGNITUDE & ANGLE FROM CHART

PARALLEL $= \dfrac{\overline{(Z_{co} \times Z_{sub})}}{Z_{ser}} \underline{/\theta_{co} + \theta_{sub} - \theta_{ser}} = \overline{Z}_{tel}\underline{/\theta_{tel}} = (R_{tel} + jX_{tel})$ COMPONENTS FROM CHART

NATURE OF CONTACT		TOTAL FAULT CIRCUIT IMPEDANCE	CONTACT AMPERES (I_c)	CONTACT VOLTS (V_c)	FUSE AMPERES (I_{fu})	FUSE DUTY (V_{fu})	SUB. VOLTS (V_{sub})	DROP-WIRE VOLTS (V_d)
OPEN-WIRE CONTACT	NO FUSE OPERATION OR PLANT BURN OFF	$(R_L + R_{tel}) + j(X_t + X_L + X_{tel}) = R_1 + jX_1 = Z_1$ FROM CHART	E/Z_1	$I_c Z_{tel}$	V_c/Z_{sub}	—	$I_{fu}R_g$	$I_{fu}R_g$
	NO PLANT BURN OFF — FUSE OPERATED	$(R_L + R_{co}) + j(X_t + X_L + X_{co}) = R_2 + jX_2 = Z_2$ FROM CHART	E/Z_2	$I_c Z_{co}$	ZERO	$I_c Z_{co}$	ZERO	$I_c Z_{co}$
	PLANT TO C.O. BURNED OFF — NO FUSE OPER.	$(R_L + R_{sub}) + j(X_t + X_L + X_{sub}) = R_3 + jX_3 = Z_3$ FROM CHART	E/Z_3	$I_c Z_{sub}$	V_c/Z_{sub}	—	$I_{fu}R_g$	$I_{fu}R_g$
	PLANT TO C.O. BURNED OFF — FUSE OPERATED	INFINITE	ZERO	E	ZERO	E	ZERO	E
AERIAL CABLE CONTACT		$(R_L + R_{co}) + j(X_t + X_L + X_{co}) = R_4 + jX_4 = Z_4$ FROM CHART	E/Z_4	$I_c Z_{co}$	—	—	—	—
CONTACT WITH DROP WIRE FROM CABLE		SAME AS OPEN-WIRE CONTACTS WITH OMISSION OF OPEN WIRE FROM TELEPHONE PLANT IMPEDANCES						

— ASSUMPTIONS —
1 — EARTH RESISTIVITY = 100 METER-OHMS
2 — SPACING OF PHASE WIRE AND NEUTRAL = 6 FEET
3 — INFINITE SUPPLY CAPACITY TO THE SUBSTATION, WITH NO PATH FOR EARTH CURRENTS

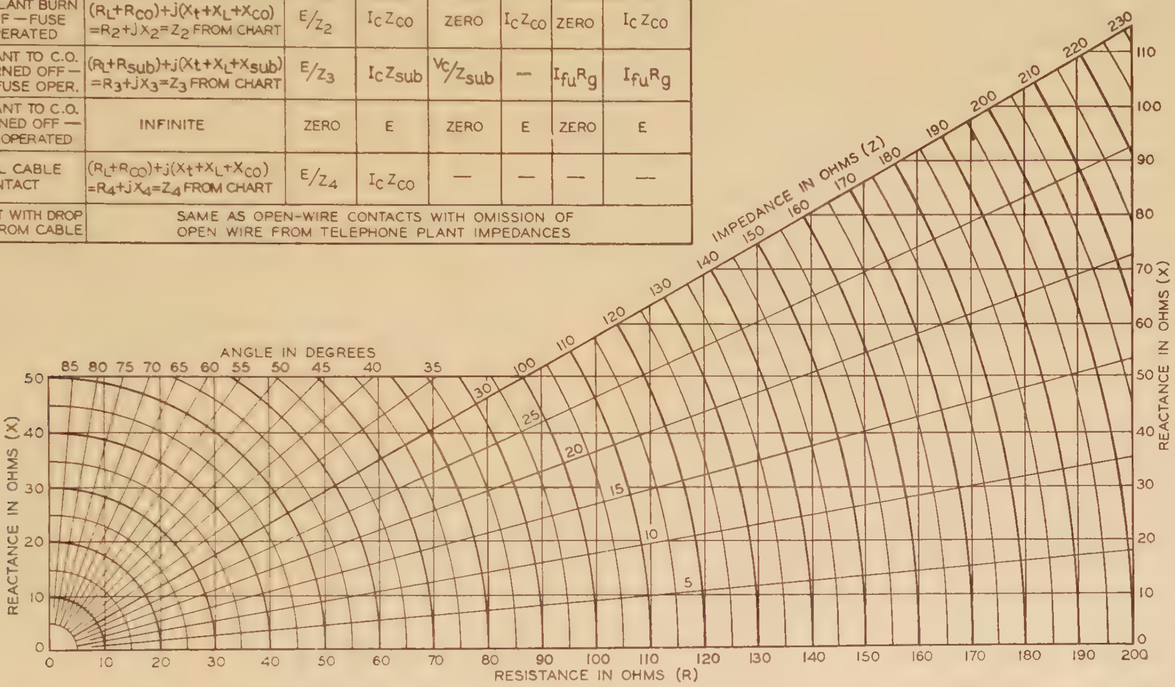


TABLE A
SUBSTATION REACTANCE IN OHMS
(TRANSFORMERS — 6 PER CENT REACTANCE)

KILOVOLT-AMPERES	X			
	4 KV	6.9 KV	11 KV	13.2 KV
100	9.60	28.57	72.6	104.54
200	4.80	14.29	36.3	52.27
300	3.20	9.52	24.2	34.85
500	1.92	5.71	14.52	20.91
750	1.28	3.81	9.68	13.94
1000	0.96	2.86	7.26	10.45
1500	0.64	1.90	4.84	6.96
2000	0.48	1.43	3.63	5.23
3000	0.32	0.95	2.42	3.49
5000	0.19	0.57	1.45	2.09
7500	0.13	0.38	0.99	1.39
10,000	0.10	0.29	0.72	1.05

TABLE B
TELEPHONE OPEN-WIRE IMPEDANCE
IN OHMS PER 1000 FEET

WIRE	R	X
0.080 CU	1.63	0.32
0.104 CU	0.97	0.32
0.128 CU	0.64	0.30
0.165 CU	0.40	0.30
0.083 STEEL	16.3	1.52
0.109 STEEL	9.5	1.52
0.134 STEEL	6.3	1.52
DROP WIRE	14.2	0.38

TABLE C
POWER-LINE IMPEDANCES FOR PHASE-TO-GROUND
FAULTS IN OHMS PER 1000 FEET

WIRE	3-WIRE CIRCUIT		4-WIRE CIRCUIT	
	R	X	R	X
4/0	0.070	0.275	0.083	0.201
3/0	0.083	0.275	0.102	0.203
2/0	0.100	0.277	0.117	0.210
0	0.123	0.278	0.144	0.218
1	0.150	0.280	0.176	0.225
2	0.167	0.280	0.214	0.235
3	0.227	0.282	0.259	0.244
4	0.284	0.284	0.312	0.256
5	0.352	0.286	0.381	0.258
6	0.439	0.288	0.467	0.259

TABLE D
AERIAL CABLE-SHEATH IMPEDANCES IN OHMS
PER 1000 FEET (SEE NOTE)

APPROX. NUMBER OF PAIRS IN CABLE				CABLE DIAMETER IN INCHES	R	X
GAUGE						
19	22	24	26			
450	800	1200	—	2.6	0.110	0.235
300	600	900	—	2.2	0.140	0.239
—	450	600	—	1.9	0.172	0.240
200	400	—	—	1.75	0.193	0.242
150	300	400	600	1.55	0.222	0.244
100	200	300	400	1.30	0.267	0.248
50	100	150	200	1.0	0.343	0.254
25	50	75	100	0.75	0.439	0.263

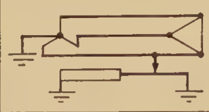
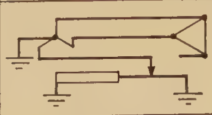
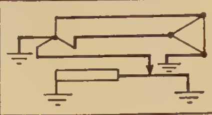
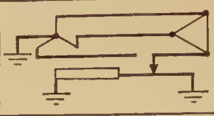
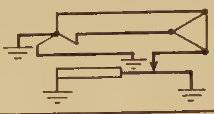
TABLE E
IMPEDANCE-TO-GROUND OF TELEPHONE
LINE TERMINATIONS IN OHMS

UNDERGROUND CABLE	(0.6 + j0.4)
WATER PIPE GROUND	(0.5 TO 3 OHMS RESISTANCE)
DRIVEN GROUND	(25 TO 150 OHMS RESISTANCE)

NOTE:— (TABLE D)
IMPEDANCE OF SHEATH ONLY. FOR 2 OR MORE CABLES ON SAME POLE, USE THE CABLE RESISTANCES IN PARALLEL, 85 PER CENT OF THE REACTANCE OF THE LARGER CABLE FOR 2 CABLES, AND RESPECTIVELY 81 PER CENT AND 79 PER CENT OF THE REACTANCE OF THE LARGEST CABLE FOR 3 AND 4 CABLES

Figure 3

6.6 KILOVOLT GROUNDED WYE

TYPE OF CONTACT	NO BROKEN WIRE	BROKEN WIRE			
		SUBSTATION-END IN CONTACT		LOAD-END IN CONTACT	
		LOAD-END CLEAR	LOAD-END GROUNDED	SUBSTATION-END CLEAR	SUBSTATION-END GROUNDED
CIRCUIT					
CONTACT CURRENT	209 AMPERES			11.8 AMPERES	
CONTACT POTENTIAL	2980 VOLTS			215 VOLTS	
FUSE CURRENT	106 AMPERES			7.6 AMPERES	
POTENTIAL FUSE MUST OPEN	3350 VOLTS			215 VOLTS	
POTENTIAL OF SUB. WIRE	318 VOLTS			35 VOLTS	

6.6 KILOVOLT ISOLATED DELTA

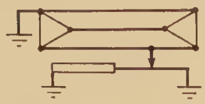
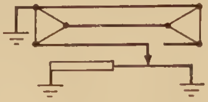
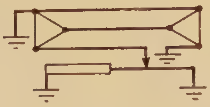
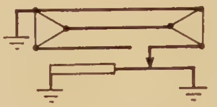
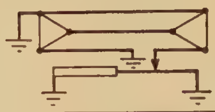
CORRESPONDING DELTA CIRCUIT					
CONTACT CURRENT	357 AMPERES			14.9 AMPERES	16.4 AMPERES
CONTACT POTENTIAL	5090 VOLTS			271 VOLTS	298 VOLTS
FUSE CURRENT	180 AMPERES			9.6 AMPERES	10.6 AMPERES
POTENTIAL FUSE MUST OPEN	5800 VOLTS			271 VOLTS	298 VOLTS
POTENTIAL OF SUB. WIRE	540 VOLTS			29 VOLTS	32 VOLTS

Figure 4

Distribution Circuit

Substation—3,000 kva
0.20 mile of 4/0 three-conductor cable
1.30 miles of 2/0 open wire
0.80 mile of number 2 open wire
0.90 mile of number 6 open wire
Substation has two 1,500-kva feeders
15 miles of circuit on each feeder
Load beyond contact—150 kva
Auxiliary fault of 0 ohm on delta system
Contact in center of number 6 wire section

Telephone Circuit

To subscriber
One-half mile of 0.109 steel
Subscribers ground—three ohms
To central office
One-half mile of 0.109 steel
One mile of one-inch cable
One mile of two-inch cable
One mile of U. G. cable

the point of contact and the underground cable plus the impedance to ground of the underground cable sheath. Any other grounds which may be connected to the aerial cable sheath should be included as paralleling impedances in determining the impedance to ground of the aerial cable sheath. Means for reducing the impedance to ground of the cable sheath are discussed later in this paper.

There is also a possibility that the suspension strand and the cable may burn off at the point of contact or at some other location depending upon the magnitude of the current and the duration of the contact. Where the severing of the cable results in the elimination of the low-impedance path to ground toward the central office, the relatively higher impedance between the contact and the subscriber may materially raise the voltage on the telephone plant.

When a contact occurs with telephone open wire, the impedance of the telephone plant is determined by the two parallel paths; one toward the central office, including the open wire to the aerial cable junction, and the aerial and underground cable sheaths; the other from the point of contact to the subscriber station, including the open wire, the drop wire, and the protector ground. If the telephone open wire parts, the impedance will be determined by one of these paths alone, depending upon which end of the telephone wire remains in contact with the power wire.

In view of its high resistance, iron telephone wire frequently may be the controlling impedance in the fault circuit, and the voltage on the telephone plant at the point of contact will approach the full voltage to ground of the power circuit. Joint use with such wire therefore presents a more difficult problem than where other types of telephone plant are involved.

Type of Contact

A contact may involve any one of five different physical situations, depending upon whether or not the power wire parts and, if it parts, which end remains in contact with the telephone plant, and whether or not the other end becomes grounded. Examples of these five situations are shown diagrammatically on figure 4 for a wye and a delta system.

It will be noticed that single faults are assumed on wye circuits, and double faults, one of which is located at the substation bus, are assumed on delta circuits. A double fault is chosen on delta circuits for two reasons: (1) a single fault ordinarily produces no appreciable voltage or current on the telephone plant and can exist without making the power circuit inoperative; (2) routine contact reports analyzed by the committee show that with delta circuits an appreciable number of double faults involving the telephone plant have occurred. A single-phase fault on a delta circuit sometimes is the forerunner of a double fault, because a ground on one phase raises the voltage to ground of the other two phases and this may cause a breakdown to ground.

From the currents and the voltages resulting from these contacts as shown on this diagram, it is evident that the fault current and voltages at a contact are greatest where the power wire remains continuous from the contact to the supply point. Hereafter in this paper when a contact is referred to, the most severe type of contact is assumed, although it is recognized that such conditions do not always obtain.

Computation of Voltage in Telephone Plant

To estimate the voltages and currents in the telephone plant resulting from a contact, it is necessary to have impedance data on the various elements involved in the fault circuit. These data are given on figure 3, which also includes formulas and curves to facilitate the computations. These formulas are for steady-state conditions and do not include transient conditions.

In the grounded-neutral systems generally the maximum voltage that can be impressed on the telephone plant is the phase-to-neutral voltage of the system, i.e., for a three-phase system the line voltage divided by the square root of three.

In a delta system, as stated above, a single fault impresses a relatively small voltage on the telephone plant. On the other hand, a double fault can impress practically full phase-to-phase voltage. However, the use of a suitable grounding bank will, in general, limit the maximum voltage impressed on the telephone plant to the line voltage divided by the square root of three. The use of a grounding bank means that a substantial voltage, up to a maximum equal to the phase-to-neutral voltage will be impressed for every contact, whereas without it a substantial voltage is impressed only when a double fault occurs.

Duration of Contact

While the duration of some contacts is short as a result of the nature of the contact (such as "side swiping" and other types of momentary contacts), in general, the duration is determined by the magnitude of the fault current and the type and setting of the interrupting devices in the power circuit. Either fuses or circuit breakers are used to de-energize the power circuits, depending on the service requirements and the general system arrangement. Frequently fuses are used to isolate faulty branches without causing an interruption to the entire circuit. From the safety standpoint it is immaterial how the fault is de-energized as long as this is accomplished promptly.

Power-Circuit Interrupting Devices

Phase or overcurrent relays or fuses must be set sufficiently high to avoid tripping the circuit under maximum load conditions. If the capacity of the circuit is relatively large, this setting may be higher than the fault currents which would result from a fault involving contact with telephone plant at certain locations. On the other hand, the current setting of ground relays can generally be lower than for phase relays, which makes it possible to de-energize a circuit for faults which would not be cleared if phase relays alone were used. Generally ground relaying has not been applied to an isolated delta system except by the addition of a grounding transformer. Under certain conditions phase relays can be so arranged and set as to provide positive de-energization.

The current value to which the ground relays can be set without false operation depends, among other things, upon the load and upon the type of circuit used, and upon the ratings of transformer and branch fuses where definite selectivity between the fuses and the relays is planned.

Ground detectors are used to some extent in connection with the operation of delta distribution circuits. These devices, which indicate a single fault on a delta system, will reduce the probability of double faults. However, in general, the same reliance cannot be placed in them as in automatic devices that are associated with a particular circuit.

When a power circuit becomes de-energized by a circuit breaker it is common practice to reclose the circuit one or more times, since tripping out may be due to a fault which clears when the circuit is de-energized. Where the fault involves telephone plant, the number of reclosures may adversely affect the situation. Holding the number of reclosures to a reasonable minimum will tend to limit the damage to the telephone plant.

Subscriber's Premises

On a subscriber's premises, the possibility of fire or electric shock due to a breaking down of the insulation on the telephone wiring can ordinarily exist only following the introduction of an excessive voltage, from whatever cause, imposed directly on the telephone plant. Practically all cases of fires or personal injury which have occurred were due to potentials causing failure of telephone plant insulation or the holdover of telephone fuses along with the power voltage remaining on the telephone circuit for some time.

In some cases, excessive voltage due to accidental contacts caused arcing, such as holdover of fuses, but the short duration of the fault did not permit the arcing to spread to other objects and start a fire. Where injury to persons has occurred it has resulted mostly from the fact that when arcing or some other disturbance attracted attention, the person attempted to use the telephone, cut wires, or extinguish fires while the telephone circuit was still energized. There are no records of such injuries having occurred where the duration of the fault was short.

Other things being equal, breakdown of insulation on telephone wiring and fuse holdovers at the subscribers' premises are more likely to occur in the event of accidental contacts with the higher voltage power distribution circuits than with the lower voltage distribution circuits. However, as pointed out in later paragraphs, means have been developed such as to avoid such occurrences in connection with higher voltage joint use.

This objective is obtained by: (1) limiting the duration of foreign voltage, (2) co-ordinating the duty imposed on the fuse and its capacity, (3) co-ordinating the voltage which may be impressed and the drop wire insulation, and (4) minimizing the potential to ground and also the differences of potential on the premises.

Central Offices

Telephone central offices are generally located in areas where extensive underground metallic structures of low impedance are available and these are used for the grounds. It is Bell System practice to bond underground cable sheaths to the central office ground, thus further assuring a low impedance.

When a contact occurs between a power circuit and telephone plant, the protector blocks at the central office will limit the potential difference within the office to the breakdown voltage of the protector block. This is true regardless of the voltage of the power circuit involved in the contact or the impedance of the central office ground. The resulting current to ground depends upon the voltage and impedance of the power circuit, and the impedance of the telephone plant from the contact to ground. The potential, to which the central office ground can be raised, depends upon its resistance and the portion of the fault current that passes through it. If the ground potential in the office, that is, the potential of the ground bus with respect to remote ground, should exceed approximately 300 volts, many of the protector blocks connected to subscriber lines not otherwise involved in the fault will break down.

Where extensive underground structures are used as the central office grounds, the probability of raising the potential of a central office to 300 volts is remote, and this is particularly true where underground cable is also present. Also, where telephone cable is involved, dielectric breakdown from sheath to conductors and between conductors will provide paths to other grounds as well as to the central office and these will further limit the voltage that may develop. However, where such low impedance grounds are not available, the situation from the safety standpoint at the central office becomes very similar to that encountered at a subscriber's premises, and the factors previously discussed in connection with such premises should be taken into account.

Safety to Telephone Employees

Considering employees working on telephone circuits on joint poles carrying higher voltage distribution circuits, attention must be given to four types of situations: (1) contact with power conductors or equipment in normal operating condition, (2) contact with a broken power conductor, (3) contact with telephone wires energized at some other location by a broken power conductor, and (4) energized poles.

With adequate clearances between power and telephone attachments, the probability of a properly trained telephone workman making contact with a power conductor is remote. Assuming approved construction, therefore, it can be said that the hazard to linemen existing under normal power circuit operating conditions is slight.

Unless the broken power wire is so located that it is difficult to see, the probability of a telephone outside plant employee making contact with it is small. These employees have definite instructions not to handle or approach a broken power conductor unless it is absolutely necessary, and then only with the proper equipment (rubber gloves, etc.). However, if one should make contact with such a wire, the probability of being seriously injured is great, but this is true for any primary power circuit voltage.

When a contact occurs between a power conductor and telephone plant, there is generally some visible evidence of this condition at the central office which gives a warning that the line has been energized and it is the usual practice to caution any lineman detailed to investigate such trouble to be on the lookout for energized wires. If, however, he actually comes into contact with such an energized telephone wire and also with some grounded object or another wire, the effect would be serious for either the lower or the higher primary voltages. The degree of safety here is more directly influenced by the duration of the excessive voltage on the telephone plant than by the magnitude of the voltage.

Current leakage along poles may result either from an insulator failure or from a loose wire resting on the crossarm or pole. A potential is then impressed upon the pole, the magnitude and gradient of which depend upon many factors, such as the contact resistance, moisture content of the pole, the resistance of the crossarm wood compared with the resistance of the pole wood, and the presence of various attachments on the pole, such as a grounded telephone cable, lamp bracket, ground wire, etc.

Where there is a grounded cable on the pole the potential to ground around the telephone space is generally quite small; of the order of 50 volts or less. Where there are no grounded cables, the potential-to-ground from the pole surface in the telephone space may be materially greater, ranging up to several hundred volts.

Tests on pole leakage were conducted by the committee on two poles under dry and wet conditions. It is recognized that test results based on measurements on two poles are not conclusive. They, however, provide sufficient qualitative information to indicate that:

(*a*). Under similar conditions the potential gradient on the pole surface increases with the increase of voltage. However, with the higher voltages, there is a marked tendency for the top of the pole to smoke or burn with the result that the fault is more likely to be detected and remedied.

(*b*). The presence of a grounded telephone cable materially reduces the voltage to ground on all parts of the pole below the location of the cable.

(*c*). The likelihood that the voltage to ground at points on the pole would reach substantial magnitudes under the condition mentioned in (*b*) without some visible indication either by smoke or flame at the top of the pole seems small, since currents of the order of one-quarter ampere give visible effects in the nature of smoke or flame.

It would seem from this that the use of higher distribution voltages under the conditions that have been discussed does not introduce any elements which would make the hazard to linemen materially different from that which exists at the lower voltages.

Damage to Telephone Plant

The costs of repairs to telephone plant as a result of contacts vary over a wide range, depending upon conditions such as type of plant, duration of contact, magnitude of current, etc. Since duration of contact has such an important bearing on the extent of damage done, it appears reasonable to expect that higher voltage joint use with provision for prompt de-energizing of the circuit will not increase and may even decrease the total cost of telephone plant damage as compared to the total cost of such damage with lower voltage circuits, where such prompt disconnection is not generally obtained.

Protective Measures

It is evident, in view of the foregoing paragraphs, that joint use with the higher-voltage distribution circuits entails consideration of a number of factors which are not involved in joint use with the ordinary distribution voltages. However, co-ordinated measures have now been developed such that the degree of safety which can be attained in many situations involving joint use with the higher distribution voltages is comparable to that involved in joint use with the ordinary distribution voltages. The protective measures which have been developed in this connection are discussed in the following paragraphs.

It is not intended to imply that all of the protective measures should be employed in every situation where higher voltage joint use is contemplated, since the solution in any specific situation will depend upon many local factors. Some of the suggestions given below may already be incorporated in the existing plants for operating reasons. The methods cover only those which have been carefully considered and applied in one or more situations. There are no doubt other means which can be employed in certain situations. Studies are of course being continued, looking forward to improvements and developments in the protective measures of both systems.

The methods and apparatus used for limiting the magnitude and duration of the fault current and voltage should be of a high degree of reliability, whether applied to the power or the telephone plant. They should also be of such a nature as not materially to affect the service of either utility. Where such current, voltage, and duration limitations are obtained as a result of the inherent nature of the circuits, or are due to devices installed for operating reasons, the degree of reliability obtained is generally greater than where such devices or methods are used primarily for co-ordination purposes. Also, the reliability of protective devices is greater for those giving positive indication when they become inoperative.

DROP WIRE AND FUSES

The use of telephone drop wire with heavier insulation and telephone fuses capable of operating properly under higher voltages and currents would provide increased protection. This added protection would, of course, have to be applied at all exposed subscribers' stations and would not reduce the voltages on the telephone plant or reduce the duration of contacts. Satisfactory drop wire with heavier insulation or fuses with a higher interrupting capacity are not economically available for general use at the present time. The use of these measures is not further considered in this paper for a general solution, as other measures appear more promising, although they may offer a solution for isolated cases.

REDUCING IMPEDANCES OF CABLES

Aerial telephone cable sheaths are generally effectively grounded by bonding to the underground cable sheath. Where the aerial and underground cables are not bonded together, a substantial bond at their junction will give the aerial cable the benefit of the low impedance of the underground cable sheath. For long, small-size aerial cables, the telephone plant impedance to ground may become relatively large. In situations of this kind, it is generally practicable to reduce the cable sheath impedance by placing auxiliary grounds on the aerial cable sheath.

COMMON GROUND FOR POWER AND TELEPHONE

The interconnection of power and telephone grounds on subscribers' premises limits differences of potential between the power and telephone wiring. In addition, it will in general provide a lower resistance ground for protection than can be practicably obtained otherwise. This lower resistance ground will, of course, tend to limit the potential on the telephone plant and to ensure sufficient current to operate protective devices in cases of contact. Such common grounding, of course, has been usual in areas where extensive piping systems have been available and both have been connected to them.

A common ground will under some conditions result in some increase in telephone circuit noise where low impedance grounded ringers are used. Where, on specific lines, noise is introduced it may be necessary to apply remedial measures.

GAPS ON OPEN WIRE

The use of protective gaps, having a breakdown voltage of about 3 kv on open-wire telephone lines provides a means for limiting the voltage impressed on the drop wire and across the station fuse, and also ensures a path to ground for fault current to operate the power system protective devices. These gaps to be effective require relatively low resistance grounds, which under certain conditions may be obtained in connection with the use of well grounded power circuit neutral grid.

BARE POWER WIRES

The use of bare, as compared with covered power conductors, where joint use with telephone open wire is involved, lessens the probability of the telephone wire parting in case of contacts due to the tendency of the wires to weld. The parting of the telephone wire would cause an increase in impedance in the telephone plant. It is desirable to maintain the low impedance to ground of the telephone plant for reclosures of the power circuit as well as for the initial contact.

Grounding Banks on 6.9-Kv Delta System

The use of a suitable grounding bank on a 6.9-kv delta system inherently limits the magnitude of fault currents and also limits to 4 kv the maximum voltage to which the telephone plant can ordinarily be subjected. The use of ground relays or low capacity fuses will ensure prompt de-energization of the circuit in case of contact with the telephone plant.

13.2-Kv Grounded-Neutral System

In a 13.2-kv grounded-neutral system the phase-to-ground voltage is 7.6 kv. For relatively low-capacity substations there is appreciable impedance inherent in the power system to limit the magnitude of fault current and to aid in obtaining a favorable impedance condition for cases of contact. For a large capacity station, feeder reactors or an impedance in the neutral will aid in obtaining favorable impedance conditions. Ground relays of a relatively low setting can be applied. For situations where the fault current may be relatively large the duration of fault can frequently be shortened by the addition of an instantaneous ground relay set to operate on a current several times larger than the setting of the inverse time ground relay.

Grounding Banks on 13.2-Kv Delta System

The use of a grounding bank makes it possible to apply ground relays to such a system which will ensure prompt de-energizing in case of a contact with the telephone plant. The voltages to ground of such a system are in general the same as the voltages to ground of a 13.2-kv grounded-neutral system. However, the magnitude of the fault current will generally be less due to the impedance of the grounding bank.

Summary

To summarize, for situations where joint use with higher voltage distribution circuits is the best engineering solution, safety conditions comparable to those existing at the lower voltages can, in general, be obtained by co-ordinating the protection of the two systems. Various combinations of the protective measures suggested in this paper, depending on the characteristics of the power and telephone plant involved, have been successfully applied to actual field cases.

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Mechanical Uniformity of Paper-Insulated Cables

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Synopsis: Application of a recently developed method whereby it is possible virtually to see the voids in the layer structure of high voltage cable insulation shows most such insulation to be mechanically irregular. Lack of mechanical uniformity in the cable as manufactured is responsible for much of the ionization after the load cycle, and probably to a great extent for ionization breakdown. Application of the method and of supplementary methods should lead to better load cycle stability, improved installation practice, and ultimately to reduced insulation thicknesses.

Introduction

THE SEARCH for ways of improving solid-type, high-voltage underground cable, so as to raise its reliability in operation to the same high level as that of other major links in power systems, has gone on intensively for the last 10 or 15 years in this country and in Europe. The characteristics of the materials of which they are made, particularly paper, oil, and lead; their design; the thoroughness of drying, degassing, and impregnating of the insulation; the deterioration in service through ionization and oxidation; the electrical characteristics before and after the load-cycle: all these have been the subject of intense research. In consequence, progress has been made in raising quality of solid cables, as is indicated by the ETL index[1] and by reduction in failure rate.[2]

Indeed, this progress has been great enough to raise the question in some quarters as to whether solid-type cable had not reached the practical limit of its development, and that therefore from now on only minor improvements might be expected. There are a number of observations which throw very serious doubt on such a point of view. One of these is the great difference in insulation thickness used respectively with solid-type cable and oil-filled or pressure-type cable. Solid cable has twice, and sometimes more than twice, the wall thickness of the pressure type for the same voltage. Is this marked difference due solely to effects of differential expansion of the oil in the solid-type cable during operation, as is usually represented? Or is it possible that, in this long-continued research, some important factor has been overlooked?

On looking back over the cable researches and the literature of dielectrics for the past 10 or 15 years, one finds that little or no information has been published concerning the compactness and uniformity of the layer structure of cable insulation. A great deal has been written about electrical uniformity, both longitudinally and radially, but nothing about mechanical uniformity. Yet it is the common everyday experience of those who dissect cable which has failed in service to find that the insulation of some cables is much looser than that of others, that wrinkles are often present, and that in three-conductor cable heavy wax deposits occur sometimes on only one shoulder of the insulation of one conductor. Poor mechanical assembly of a similar nature is noticed in dissecting cables in the laboratory after load-cycle aging. Earlier studies in which dyed oil was forced through short lengths of cable showed that there were preferential channels in the insulation wall itself.[3] Experimental work with cables in which voids were kept from forming by the application of fluid pressure has revealed the presence in the insulation of tight and loose annular zones. There is thus a great deal of field and laboratory observation which indicates cable insulation to be frequently nonuniform in its layer structure.

How general are mechanical irregularities in cable insulation, and what is their significance in terms of operation and life? Is mechanical nonuniformity a factor of importance in solid-type cable which heretofore has been overlooked? To answer these questions an investigation was undertaken. As a first step, quantitative methods of measuring irregularities in the insulation wall were developed. One of these is a particularly powerful tool because it makes possible the quantitative visual examination of the cable structure at any selected point. When these methods were applied, a great many defects of design and of mechanical assembly in practically all modern cable became apparent. Further study showed these irregularities to be related quite closely to electrical characteristics. Much effort was expended in interpreting mechanical nonuniformity in terms of manufacturing technique. It is the purpose of this paper to present these new test methods and the results of their application to a large number of new and used cables.

Methods

In the attempt to find some quantitative way of evaluating the mechanical characteristics of cable insulation, early efforts were centered on the development of simple mechanical tests on the cross section for measuring average compactness and for detecting tight and loose annular zones in the laminated dielectric. At this stage the difficulties involved in obtaining reliable measurements on spongy oil and paper insulation seemed insuperable. Later, microscopic studies gave a clue which, when followed up, led to a new technique which makes it possible to prepare thin translucent cross sections of wafers. These show the internal structure of a cable at a glance. The insight into cable design and construction afforded by the wafer method was so great that it was decided to spend most of the available time on its perfection. As a

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D. L. SMART and J. M. REYNAR are affiliated with The Detroit Edison Company, Detroit, Mich., and K. S. WYATT recently resigned after many years' association with that company, to join a manufacturing organization in England.

1. For all numbered references, see list at end of paper.

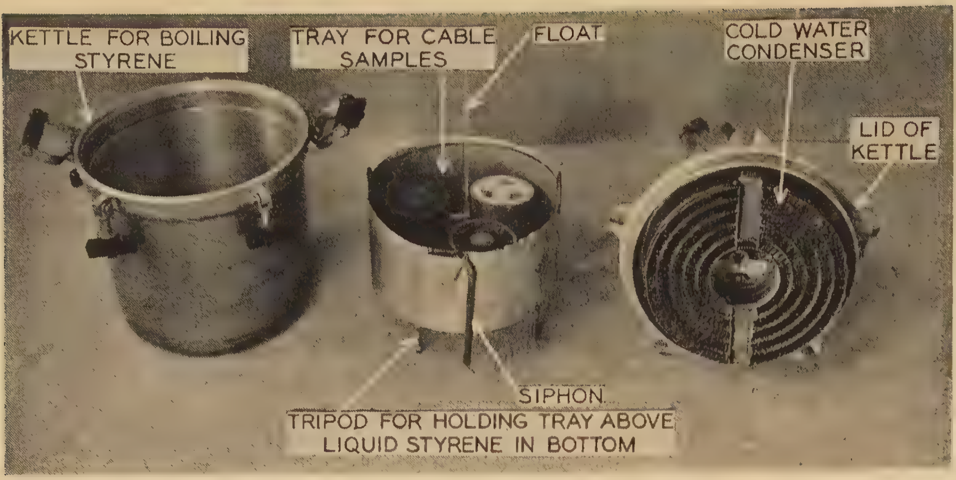
KETTLE FOR BOILING STYRENE
TRAY FOR CABLE SAMPLES
FLOAT
COLD WATER CONDENSER
LID OF KETTLE
SIPHON
TRIPOD FOR HOLDING TRAY ABOVE LIQUID STYRENE IN BOTTOM

Figure 1. Oil extraction and styrene impregnation apparatus for preparing translucent cable cross sections; apparatus disassembled

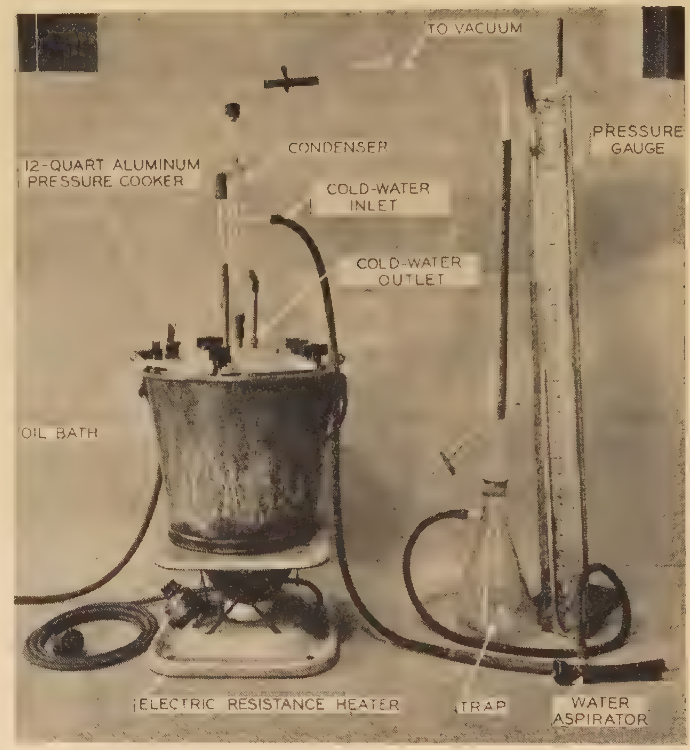

Figure 2 (below). Oil extraction and styrene impregnation apparatus for preparing translucent cable cross sections; general view

consequence the mechanical test methods referred to above were not carried to the same degree of refinement; nevertheless, each of the tests to be described is capable of yielding reliable and useful information.

PENETROMETER METHOD

A simple method of determining general compactness is to drop a weighted needle into the cable cross section at chosen points, measuring the depth of penetration. For this purpose the special sharp-pointed five-degree needle of a chemical penetrometer is adjusted so as just to touch the insulation, and then, released by means of a mechanical trip, a 150-gram weight is dropped through about one centimeter, driving the needle into the insulation. Although the method is useful in making rough comparisons of the compactness of different insulations, it is most valuable for evaluating the density of the filler spaces, this being an important factor in compound migration in cable laid on slopes and in the behavior of cable during load-cycle aging and use.

It is important, in this and the two succeeding mechanical tests, to prepare the sample carefully. In cutting the sample, the length of which has been standardized at two and one-half inches, a sharp bandsaw is used so as not to disturb the layer structure. Since in some cables the sheath constricts the insulation, it seems desirable to make a longitudinal saw cut so as to just sever the lead but not the binder tape. Exposure of the cable end to air for more than 30 minutes results in swelling of the layer structure due to moisture absorption, and consequently to erroneous values of compactness; hence samples should be stored in jars away from the air.

THE PUSH-OUT METHOD

A second method of measuring insulation compactness is to push out the conductor of a short length, recording the pressure required and observing the shape of the insulation cone so produced. A uniform insulation should yield a smoothly stepped cone, whereas the presence of loose zones should be indicated by wide steps in the cone. The test is carried out by a simple instrument consisting of a worm-operated push-out shaft into which has been built a dynamometer and which is equipped with an end-piece of the same shape and cross section as the cable conductor. A table, having at its center a hole sufficient to pass the pushed-out insulation, is provided for holding the sample, and three adjustable fingers support the shielding tape and outer layer of insulation of the cable sample. In use, the shaft is moved downward for a distance of three centimeters at a uniform speed (about ten centimeters per minute), forcing out the conductor and coning the insulation, the maximum pressure required being observed. The test is useful only as a quick means of detecting relatively large variations in compactness of the insulation, i.e., for revealing exceptionally loose annular zones, the pressure readings being a more valuable criterion than the shape of the cone.

THE TORSION METHOD

A more delicate method of measuring compactness of the layer structure depends on the fact that, when a small flat probe is inserted between the paper layers, the force required to twist it through a small angle is much greater for compact than for loose insulation. Since the twisting forces are small, a torsion wire dynamometer was employed in the construction of the apparatus. The latter consists of a torsion head (from a Cenco de Nouy tensiometer) connected by a number 24 AWG piano wire or drill rod to a pin-vise coupling carrying the probe, and a fixed scale from which the angle of rotation of the coupling may be read. The probe, made from the end of a jeweler's hacksaw blade, has an active length of one-half inch and is 9 by 15 mils in cross section, one end being ground to a diamond shape. In use, the pointed end of the probe is inserted in the insulation to a depth of one-half inch and the force required to twist it through a 30-degree angle is determined from the torsion head scale reading. If readings are made at intervals across the insulation wall corresponding to about five layers thickness (the distance being measured with a finely graduated scale from a marked conductor strand), a radial curve from conductor to sheath for insulation compactness is obtained. The method is sufficiently sensitive to detect minor variations in tightness of layer structure, and hence is extremely valuable in studying the mechanical structure of cables, particularly after the general structure has been inspected by the wafer method to be described below; it yields important information which the wafer method does not give.

THE WAFER METHOD

An effective way to detect mechanical irregularities in cable insulation is to prepare cross-sectional cable wafers sufficiently thin to be translucent. Until recently there has been no way of accomplishing this because long before the wafer could be made sufficiently thin the insulation would fall apart. Even had it been possible to prepare thin wafers by ordinary methods the layer structure would have been so distorted that interpretation of the irregularities would have been meaningless.

A satisfactory solution has been developed. A short length of cable is first "petrified" so as to hold the layer structure in place; and ordinary mechanical methods are then used to cut out cross sections 5 to 50 mils in thickness. "Petrification" is accomplished by the use of a synthetic resin, styrene, which has recently become commercially available in liquid form.[4] Styrene has three characteristics which fit it for the preparation of cable wafers: it is highly soluble in ordinary insulating oils so that it can be used to extract and replace the oil in cable insulation; it changes on heating from a liquid to a clear water-white solid without the evolution of gas, moisture or other products, thus making it possible to "freeze" the layer structure in place; and it has no harmful effect on cable paper so that it does not distort the cable structure.

Study of wafers from a wide variety of cables shows that the method makes clearly visible tight and loose zones in the insulation, voids in which ionization may occur, wrinkling, poor cabling in three-conductor cables, errors in design, and many other important characteristics. Wafers may be used to reveal the effects on the insulation structure produced by service aging, load cycling, and bending. From a study of the wafer it is possible to reason back to the manufacturing processes and machinery used in the construction of the cable.

Preparation of Sample. A three-inch length is cut with a sharp bandsaw, care being taken not to disturb the layer structure. As before, the open ends must be protected against moisture from the air to prevent swelling which would increase the time of extraction and possibly distort the insulation structure. This is most easily accomplished by submerging the sample in liquid styrene immediately after cutting.

Extraction. Extraction is carried out in a modified Soxhlet extractor consisting of a 12-quart boiler in which styrene, vaporized in the bottom, condenses at the top and drips onto the cable samples which are supported on a tray. The latter is provided with a syphon which peri-

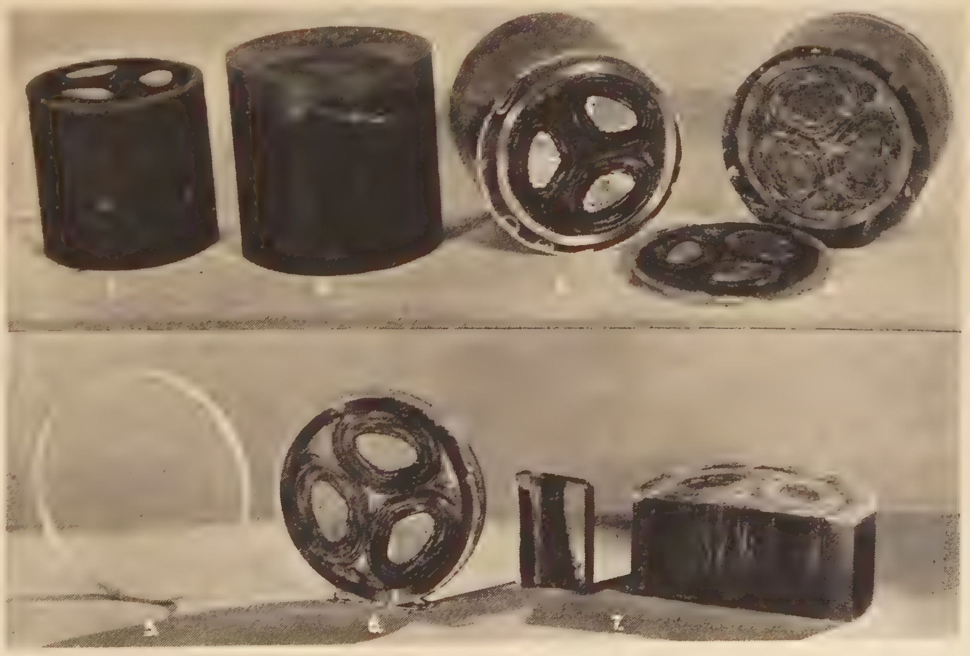

Figure 3. Preparation of a cable wafer by steps

1—Sample cut from cable and ready for extraction

2—Sample after polymerization

3—Sample with one face machined in lathe

4—One-sixteenth inch thick cross section with machined face cut from sample with band saw

5—Lucite disk to which machined face of one-sixteenth inch cross section is cemented

6—Finished cross-sectional wafer after other face has been machined and wafer reduced to proper thickness

7—Longitudinal wafer in preparation

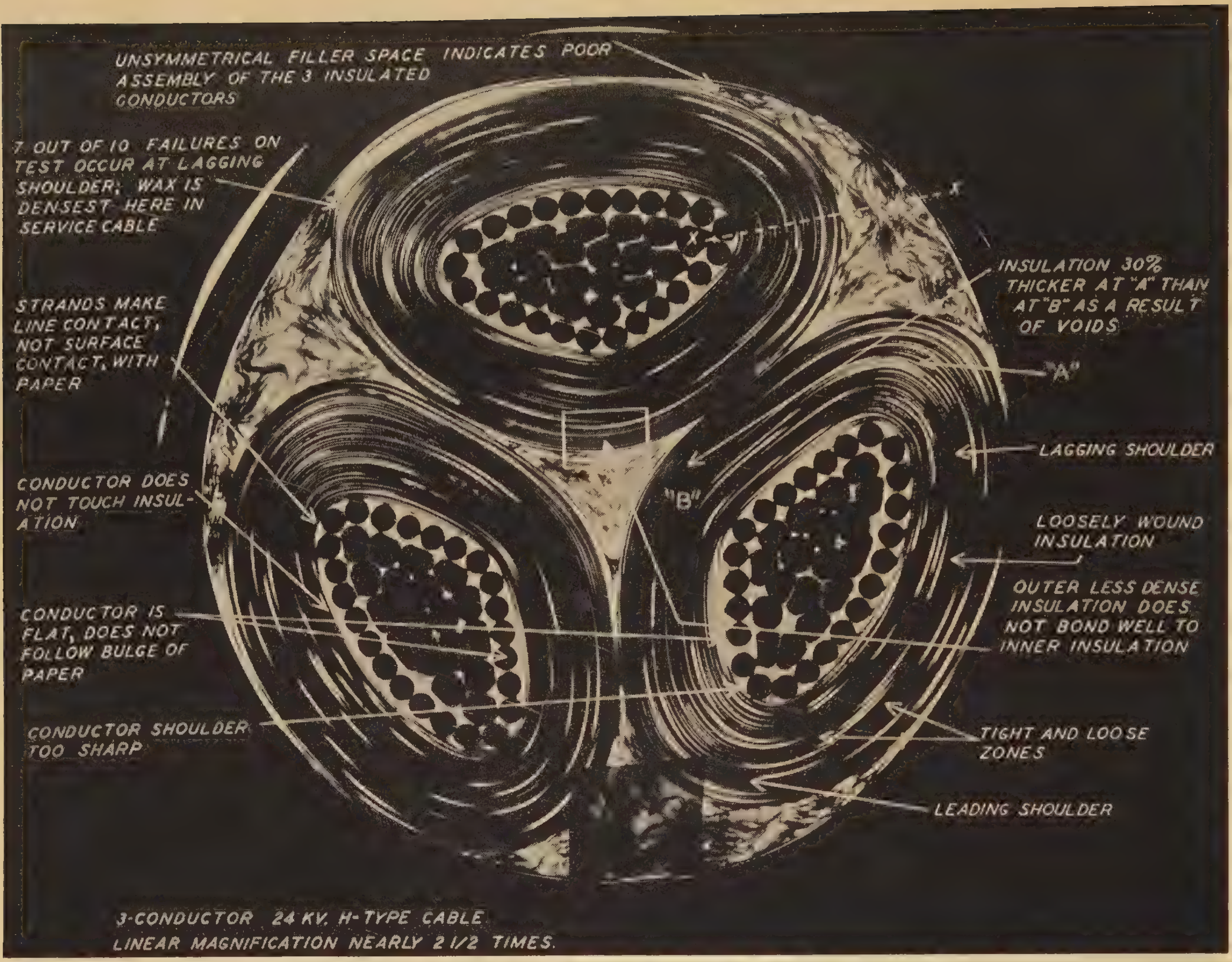
UNSYMMETRICAL FILLER SPACE INDICATES POOR ASSEMBLY OF THE 3 INSULATED CONDUCTORS
7 OUT OF 10 FAILURES ON TEST OCCUR AT LAGGING SHOULDER; WAX IS DENSEST HERE IN SERVICE CABLE
STRANDS MAKE LINE CONTACT, NOT SURFACE CONTACT, WITH PAPER
CONDUCTOR DOES NOT TOUCH INSULATION
CONDUCTOR IS FLAT, DOES NOT FOLLOW BULGE OF PAPER
CONDUCTOR SHOULDER TOO SHARP
X
X
INSULATION 30% THICKER AT "A" THAN AT "B" AS A RESULT OF VOIDS
"A"
"B"
LAGGING SHOULDER
LOOSELY WOUND INSULATION
OUTER LESS DENSE INSULATION DOES NOT BOND WELL TO INNER INSULATION
TIGHT AND LOOSE ZONES
LEADING SHOULDER
3-CONDUCTOR 24 KV. H-TYPE CABLE
LINEAR MAGNIFICATION NEARLY 2 1/2 TIMES.

Figure 4. Wafer showing typically nonuniform insulation of three-conductor, 24-kv cable

odically returns the styrene and extracted oil to the bottom of the vessel (figures 1 and 2).*

The extraction must be carried out at a pressure of about one inch of mercury, since styrene polymerizes below its atmospheric boiling temperature (146 degrees centigrade). Vacuum is obtained by connecting the system to a water aspirator, a trap and a manometer being included in the line. In order to insure complete condensation of styrene vapors, a glass condenser is inserted in the vacuum line immediately above the boiler, the cooling water circulating first through the glass condenser outside the boiler and then through the metal condenser inside. The hole in the center of the radiator core should be blocked off by soldering in a circular piece of sheet metal so as to reduce styrene evaporation losses.

The sample tray is made by cutting down to a depth of four inches, a tin or aluminum kettle whose diameter is one-half inch less than the inside diameter of the boiler. An inverted U-shaped five-sixteenths-inch copper syphon tube is soldered into a hole near the top of the side wall of the tray with one leg extending to within one-eighth inch of the bottom of the tray on the inside, and the other leg extending to one-half inch below the bottom of the tray on the outside. The tripod which supports the tray above the styrene has a height of three and one-half inches. In order to determine during operation when the tray is full of styrene, and whether the syphon is working, it is necessary to install a float. This may consist simply of a cork impaled on a rigid wire which extends into the middle of the glass condenser tube. The boiler is heated in a glycerine or oil bath so that overheating, and consequent slow polymerization of the styrene, does not occur.

In operation, styrene is poured into the bottom of the kettle in an amount 50 to 100 per cent in excess of that required to fill the tray when filled with cable samples (about 1,500 cubic centimeters total); to this about one per cent by weight of powdered sulphur is added to reduce polymerization of the styrene. The cable samples are placed in the tray, a coarse wire grid being first laid on the bottom to make extraction more easy. Dead spaces in the tray may be filled with glass rods to reduce the amount of liquid. Vacuum is applied until the internal pressure is about one inch of mercury and heating of the kettle is delayed for a few minutes in order to prevent foaming. After 8 hours, the samples should be reversed end for end, and the oil and styrene solution in the bottom of the kettle should be replaced by fresh styrene. Oil-extraction and styrene impregnation will be complete in 48 to 72 hours depending on the nature of the samples. The boiler is then opened up at a time when the tray is nearly full of styrene so as to prevent contact of air with the samples. The tray is lifted out and the samples transferred to the polymerizing vessels.

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* *Boiler* may be obtained from National Pressure Cooker Co., Eau Claire, Wis. *Metal condenser* is a circular Harrison automobile heater core about $8^1/_2''$ in diameter by 2" deep, core no. 3107381.

The syphon operates in cycles of about 10 to 15 minutes' duration when the temperature of the outside bath is 130 degrees centigrade, that of the styrene and oil in the bottom of the boiler about 65 degrees centigrade and that of the liquid in the tray about 55 degrees centigrade. The extraction temperature of 55 degrees centigrade may not be sufficient to remove all the rosin from cables containing large amounts. This difficulty may be overcome by raising the pressure and thus increasing the extraction temperature. Cycling may be interrupted by boiling of the styrene in the tray if the boiler is submerged more than one and one-half to two inches in the oil bath.

It is important to use 100 per cent pure styrene free from inhibitor other than the added sulphur. The setting qualities of each shipment should be tested by placing ten cubic centimeters in a closed test tube for 16 hours at 120 degrees centigrade, when it should have become solid. If pure, the refractive index should be between 1.5437 and 1.5440. The sytrene should be freed from moisture by passing it through a column of anhydrous sodium sulphate. Styrene may be recovered from the styrene-oil mixture by vacuum distillation so that it may be used over again. However, care should be taken not to let air contact the styrene more than necessary; otherwise oxidation products may be formed which will interfere with polymerization.

Polymerization. Each cable sample is transferred from the extraction tray to a tin can of suitable size. It is elevated above the bottom by means of three small pieces of lead cable sheath or other non-absorbent material and carefully centered by inserting three U-shaped strips of lead between the sample and the walls of the can. Styrene is then added until the cable sample is covered and the can is nearly but not quite full. The styrene is then boiled for 15 minutes by placing the can in an oil bath at about

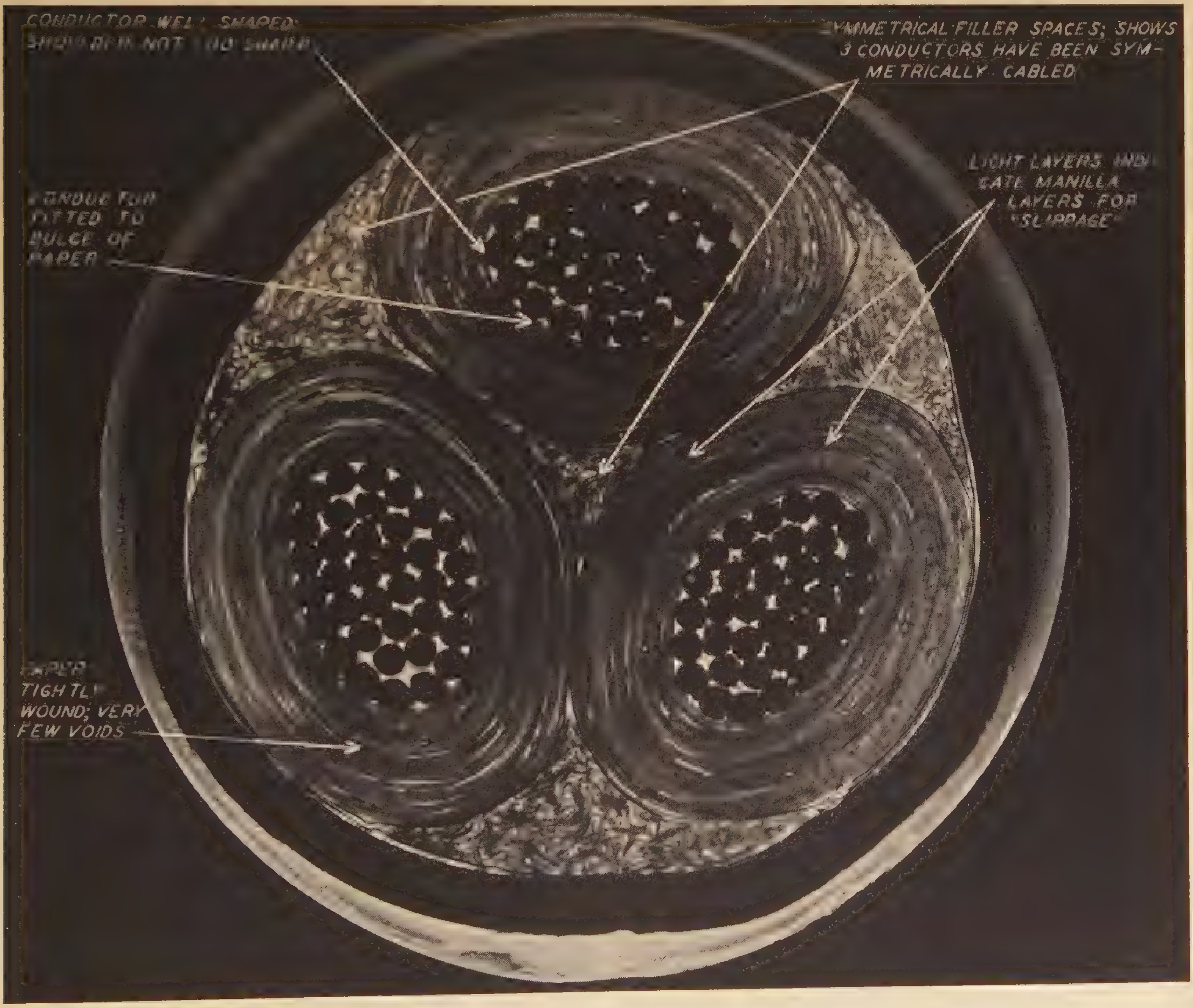

CONDUCTOR WELL SHAPED; SHOULDER NOT TOO SHARP
SYMMETRICAL FILLER SPACES; SHOWS 3 CONDUCTORS HAVE BEEN SYMMETRICALLY CABLED
CONDUCTOR FITTED TO BULGE OF PAPER
LIGHT LAYERS INDICATE MANILLA LAYERS FOR "SLIPPAGE"
PAPER TIGHTLY WOUND; VERY FEW VOIDS

Figure 5. Wafer showing typically uniform insulation of three-conductor, 24-kv cable

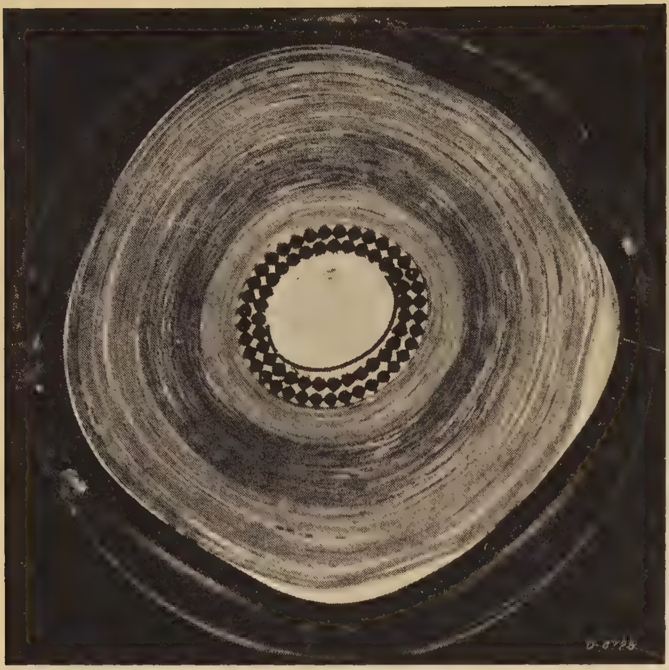


Figure 6. Wafer of 132-kv oil-filled cable of European manufacture

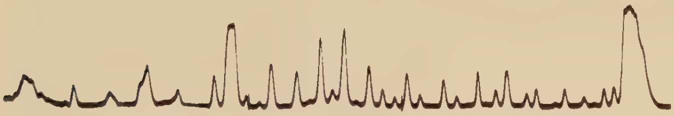


Figure 7. Radial densitometer curve taken across upper shoulder of right-hand core of insulation shown in figure 4

155 degrees centigrade. Immediately after removing the can from the bath it is made vacuum-tight by means of a lid pressed on with a standard can sealer. The styrene is then polymerized by immersing the can for 48 to 72 hours in a well-stirred glycerine or oil bath maintained at 120 degrees centigrade. After polymerization the can and its contents must be cooled slowly over a period of several hours, preferably by cooling the oil bath. After cooling is complete the can is removed from the bath and stripped from the hardened block of clear styrene containing the cable sample.

If the styrene is not completely polymerized, it will "craze," i.e., the surface will take on a whitish appearance after a few weeks' exposure. If cooling is too rapid, small cracks will appear at the surface. Continuing the polymerization for longer than 72 hours will not impair its mechanical properties. The temperature of the polymerization may be reduced but the time required will be roughly doubled for each 10 degrees centigrade decrease.

Mechanical Preparation. To prepare a wafer, the styrenated cable is cut in the middle with a metal-cutting bandsaw. To obtain a square cut it is necessary to use a carriage. First a cut one-half inch deep is made all round by turning the sample to several positions. Then a deeper cut is made all round, after which the final cut is made.

Conditions must be right for making satisfactory cuts on the bandsaw, because the styrene gums on heating. A sharp saw with hardened edge, having eight to ten teeth to the inch and traveling 1,200 feet per minute, will make about eight satisfactory cuts of a three-conductor, 350,000-circular-mil, 24-kv, styrenated cable.

The face of one-half of the sample is then turned on a lathe. The speed may be as high as 600 rpm if the sample, particularly the conductors, is cooled before each cut with a stream of carbon dioxide from a pressure cylinder of the syphon type. For roughing, cuts up to 10 mils may be made; and for finishing, cuts of one-half mil with one mil a maximum. Stellited tools are the most satisfactory. The best tool for roughing is one that is V-pointed; and for finishing, one that is sharp-edged, round-pointed, with 35- to 40- degree top rake, 35- to 40- degree side rake and 6- to 10- degree clearance.

A cut is then made with the bandsaw one-twentieth to one-tenth inch away from the finished face, the latter being pressed against a supporting face on the saw carriage. Before making this cut it is advisable to cool the conductors with a blast of compressed carbon dioxide. The lathe-finished face is cemented to a one-fourth inch disk of transparent synthetic resin such as Lucite, using syrupy styrene (prepared by boiling styrene away from air for an hour or more or until it becomes viscous). To set the cement it is necessary to place the wafer in an oven maintained at 60 to 65 degrees centigrade and to heat it for not less than 12 hours. A weight is placed on top of the wafer. To prevent warping of the Lucite, it is essential that it be placed on the plane face of a sheet of metal or glass.

The disk with the styrene wafer cemented to it is cooled and then placed in the lathe. The rough sawn face is turned down until the wafer is sufficiently translucent to

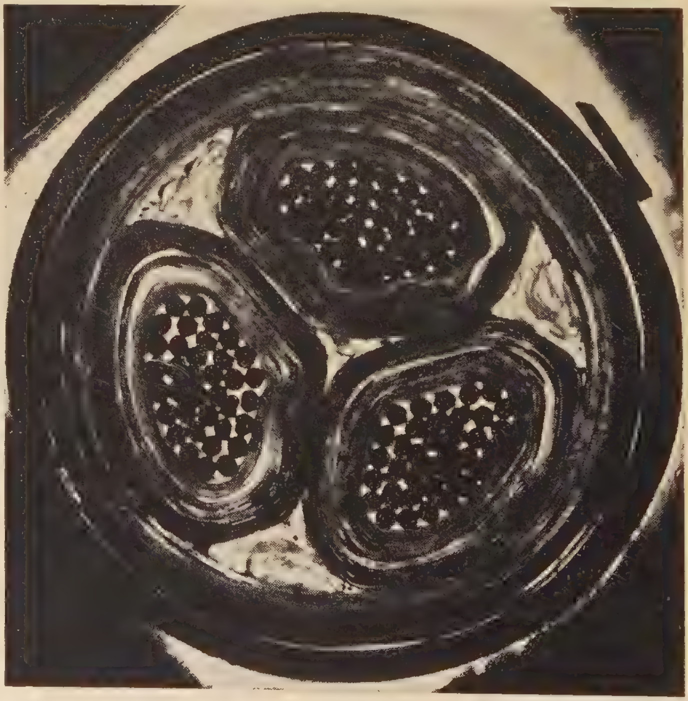


Figure 8. Wafer of three-conductor cable of European manufacture

show up all defects in its structure. It is usually necessary to turn down only to 30 or 40 mils thickness, although it is possible to produce wafers as thin as five to ten mils. Carbon dioxide cooling is resorted to between each cut as before. It should be noted that it is possible to cool the wafer too much with the result that the cement is cracked.

As a final step, a coating of transparent moisture-resistant lacquer should be given the wafer directly after it is finished to prevent swelling of the paper through moisture absorption. A coating of syrupy styrene heated over night at 60 degrees centigrade serves the purpose satisfactorily.

The various steps in making a cable wafer are shown in figure 3.

Application of Cross-Sectional Wafer Method

In analyzing wafer structure it is sufficient for most purposes to view the wafer against a strong light. Detailed study is rendered easier by the use of an enlarged photograph made by transmitted light, using antihalation film. However, for the manufacturing engineer who is familiar with the fine details of taping machinery and general fabrication processes, much additional information may be gained by more quantitative methods. Precise measurements of the layer structure may be made by transmitted light with a traveling microscope employing a magnification of 20 to 30 diameters. A binocular microscope with calibrated eyepiece is ideal.

Analysis of Typically Nonuniform and Uniform Cable Wafers

After waferizing about 100 cables it became apparent that the presence of mechanical imperfections was the rule rather than the exception and that in most cases the irregularities were sufficiently prominent to be seen immediately on casual inspection. This was true even in the case of new cable of recent manufacture. A wafer of a typically nonuniform cable photographed by transmitted light is shown in figure 4. A number of irregularities are immediately apparent. Starting at the conductor, it is seen that the paper makes line contact with the outer strands instead of surface contact, thereby increasing the electrical stress. The gaps between insulation and conductor at the flats on either side of the conductor apices indicate that the conductor is not properly shaped to conform to the natural bulge in the paper. A gap between the insulation and conductor is visible at the base of the sector of one conductor. The insulation is, in general, very loose, particularly at shoulders of the conductors. A group of five or ten tapes next each conductor is unusually slack. Many groups or bunches of tapes, which are themselves fairly compact, are separated from each other by gaps or by a number of loose tapes, giving the insulation the appearance of a series of tight and loose annular zones. The metal shielding tapes are loose, failing adequately to protect the insulation. The lateral filler spaces are unsymmetrical.

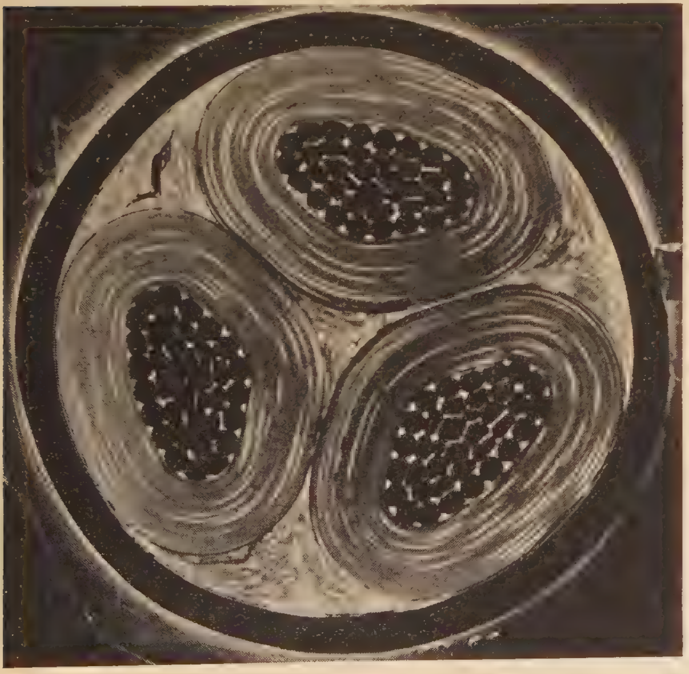


Figure 9. Wafer of three-conductor, 24-kv cable showing effect of pretwisted conductor on insulation characteristics

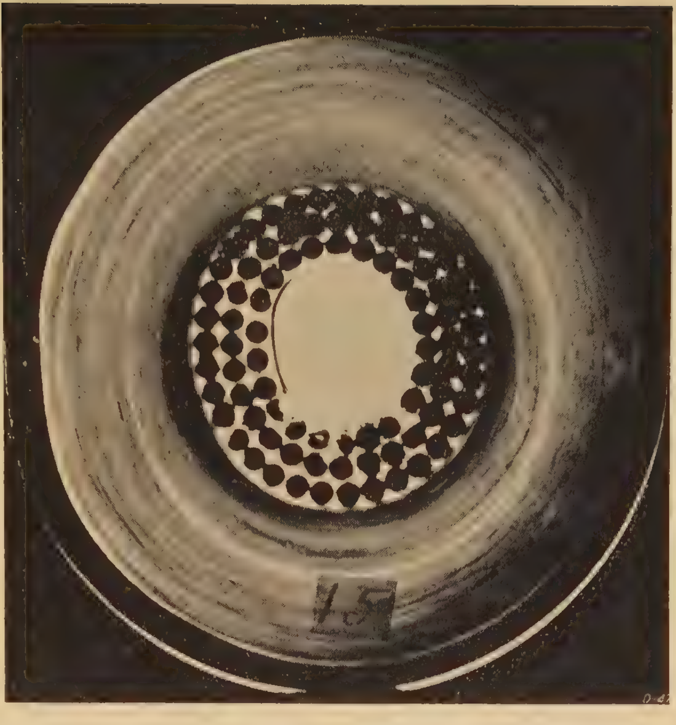


Figure 10. Wafer of 132-kv oil-filled cable showing gap between papers of different density

A wafer of a typically uniform cable is shown in figure 5. Although many mechanical imperfections are in evidence, the gross irregularities which were pointed out in connection with figure 4 are absent.

Before going into the causes of the irregularities in cable insulation as revealed by waferizing, it should be pointed out that experience in making over 200 wafers shows that they are not the result of the styrenation process, but were actually present in the original sample. Although styrene in polymerizing from the liquid to the solid form shrinks about 13 per cent by volume, most of the change occurs in the liquid stage, and even as polymerization nears completion in the 120 degrees centigrade bath, the styrene can flow longitudinally between the layers of the three-inch sample, filling up voids which would otherwise form. Since impregnation temperatures of 120 degrees centigrade are reached during manufacture, there should be no distortion as a result of the polymerization temperature; and the preliminary boiling treatment at 146 degrees centigrade is so short that its effect is believed negligible. No difference was observable in the wafer structure when the short boiling treatment was omitted and polymerization carried out at temperatures below 120 degrees centigrade. Wafers from different lengths of a uniform cable, made several months apart, all show the same uniform structure; similarly, wafers from nonuniform cable always show characteristic nonuniformities. The visible irregularities in the wafer, therefore, are not due to the process of preparation, but are characteristics of the insulation.

Certain precautions in the preparation and interpretation of wafers must be emphasized. As in any other method of analysis, reasonable care must be exercised. It is possible to make a good cable appear bad by the wafer method if the cable from which the sample is taken has been badly treated mechanically, if the wafer is sawn from the end instead of from the middle of the styrenated sample, or if excessive heat is generated in sawing off the wafer. Likewise a bad cable might appear good if the rosin were not completely extracted or if the wafer were cut too thick. It is most important to emphasize once again the necessity for keeping the finished wafer protected against moisture absorption with a film of nonabsorbent varnish.

Interpretation of Wafer Structure in Terms of Cable Design and of Manufacturing Processes

The mechanical irregularities visible in the wafer structure may be interpreted in terms of both manufacturing design and processes and of installation and operation. Among the former the effects of design, taping, and cabling machinery, and the shrinkage characteristics of the paper should be emphasized.[5]

Considering first design, the shape of the conductor is important in obtaining a uniformly compact insulation. While a round conductor offers little difficulty, the extreme sector of figure 4 is a source of trouble; had the "flats" on either side of the apex been rounded to meet the bulge in the insulation the gaps at this location would have been eliminated, and had the shoulders been less sharp there would have been less tendency to form interlayer spaces in the adjoining insulation wall. Tangential contact of the paper with the strands may be avoided by the use of crushed compact conductors (see figure 9), or perhaps by using softer papers and applying them with greater tension.

The taping machinery is responsible for many irregularities. The use of too low a tension on the individual tapes or of too high a speed of the machines results in loose insulation with visible spaces between layers. An example of loose insulation may be seen in the wafer (figure 6) of a new foreign cable submitted for test. Irregular values of tension of the different tapes may result in tight and loose zones (as in figure 4). The sudden stoppage of improperly designed machinery may loosen some of the tapes for a short distance producing wrinkles or other irregularities. The effect of difference in taping action at adjacent taping heads, and in European cable the effect of reversal of direction of taping, manifests itself in periodic variations in compactness across the insulation wall. The periodic effect was brought out clearly in the case of the wafer of figure 4 by passing a positive transparency of the photograph through a densitometer across the insulation wall at *A*. The resultant graph is shown in figure 7.

Cabling or spiralling of the three insulated cores of three-conductor sector type cable may distort the insulation walls. In order to twist the copper conductors, considerable torsional forces are applied to the insulation wall by metal guide shoes as the three insulated conductors are slowly rotated and enter the closing-in die which forces the three cores, together with the fillers, into a compact construction. It is during this rotation that any slack in the insulation is pushed away from the leading shoulder toward the lagging or trailing shoulder, the compressed leading shoulder and the extended lagging shoulder giving an effect which may be likened in extreme cases to the compressed head and extended tail of a comet. According to this explanation, all three tails should be in phase. Actually in figure 4 only two are in phase, the third, that of the lower left-hand conductor, being reversed. This may be explained by the "over-twist" which is given to one conductor by the guide shoe or die in order to make it lock in place with the other two conductors. The slack in the insulation in this case results in a 30 per cent increase in insulation wall thickness at the "comet's tail."

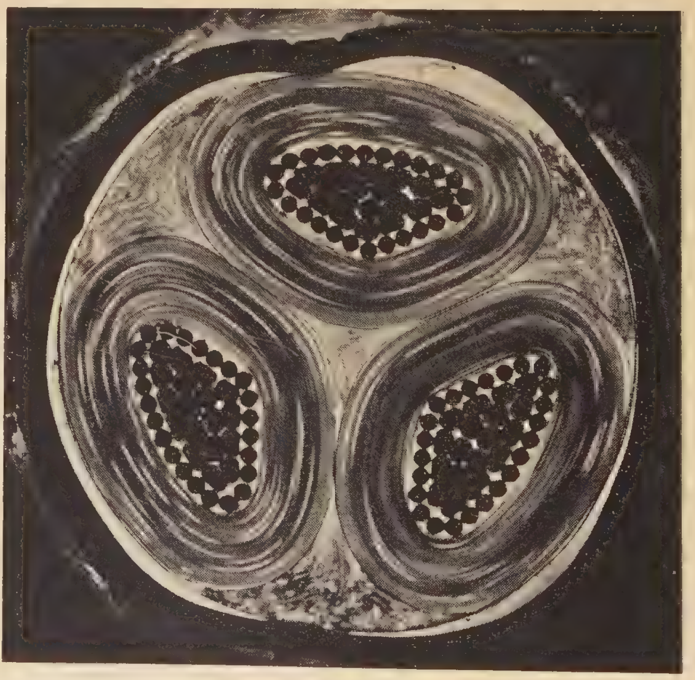


Figure 11. Wafer of cable after load-cycle aging at maximum sheath temperature of 89 degrees centigrade

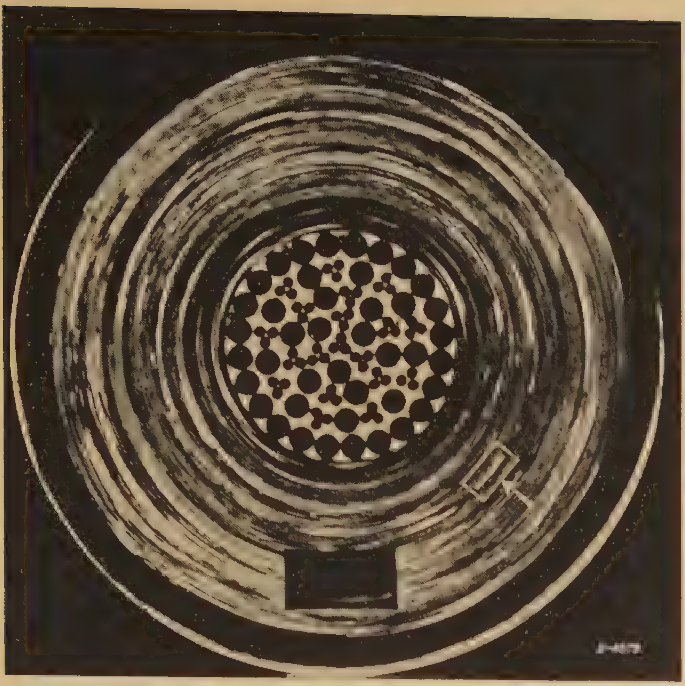


Figure 12. Wafer of single conductor 66-kv cable after load-cycle aging

In a similar cable as much as 40 per cent greater thickness has been found. A striking example of the "comet's tail" effect was found in a piece of new foreign cable submitted for test (figure 8). Pretwisting the copper conductors eliminates the rather considerable twisting forces on the insulation with the result that "comets' tails" are less likely to be found (figure 9).

Occasionally the three cores are not spaced symmetrically as a result of improper adjustment of the guide shoes or dies in the cabling machine. This trouble may usually be detected by unsymmetrical lateral filler spaces as in figure 4. The consequence is increased diameter of the cable and perhaps distortion of some parts of the insulation wall. Cabling is also frequently responsible for wrinkling.

An important cause of mechanical irregularity of insulation lies in the shrinkage characteristics of kraft paper when dried. When two different papers which have been conditioned at the same relative humidity are dried together, one may contract more than the other; for example, in "graded" insulation, if the inner denser paper shrinks more than the outer more porous paper, a gap appears such as is indicated in plate 4. Sometimes due to lack of preconditioning the paper tapes have different moisture contents at the time they are applied to the cable, and as a result differential shrinkage occurs on drying, and interlayer spaces, such as are visible in the wafers, are formed. Since paper conditioned at high humidities shrinks more than paper conditioned at lower humidities, cable made on days of high humidity, such as might occur during the summer, differs with respect to compactness of layer structure from cable made under low humidity conditions. In building insulation walls of more than 100 tapes' thickness it is often necessary to pass the conductor through the taping machine twice; if the first tapes are applied on a day of high humidity and the final tapes on a day of low humidity, a gap may be formed between the two groups of tapes during drying, because the inner tapes being more moist would show greater shrinkage. Such an explanation may account for the plainly visible gap of figure 10, although the same effect might be produced by using graded insulation of different shrinkage characteristics, or by making the second pass through a different taping machine.

Interpretation of Wafer Structure in Terms of Installation and Service Conditions

When cable which has been withdrawn from service is waferized, interlayer voids are usually visible; these may have been formed, however, not during manufacture, but during installation and use. Installation involves reeling and unreeling, bending and pulling; and operation involves load cycles. The effects of bending and of the load cycle have been evaluated by the wafer method.

Bending. Two makes of 1937 cable were subjected to the standard cold bending test specified by the AEIC. Examination of wafers made before and after the bend test revealed that, although slight changes in structure were apparent under the microscope, the additional irregularities due to bending were so small in comparison with normal imperfections as to be negligible.

Load Cycle. The effects of service can perhaps best be determined by studying wafers of cables which have been subjected to severe load cycles in the course of accelerated aging. The effect on the cable structure of load cycles having a maximum sheath temperature of about 90 degrees centigrade is shown by the wafer of figure 11. When this was compared with the wafer of the new cable it was seen that the layer structure had been opened up, and that the lead sheath which initially fitted the insulation closely had been greatly expanded. In addition, the shielding tape, which tends to resist the distention of the insulation on load cycling, had been slightly stretched. A similar cable, subjected to sheath temperatures of 70 degrees centigrade during load-cycle aging, showed about the same degree of loosening of the layer structure, but the distortion of the lead sheath was less pronounced. On the

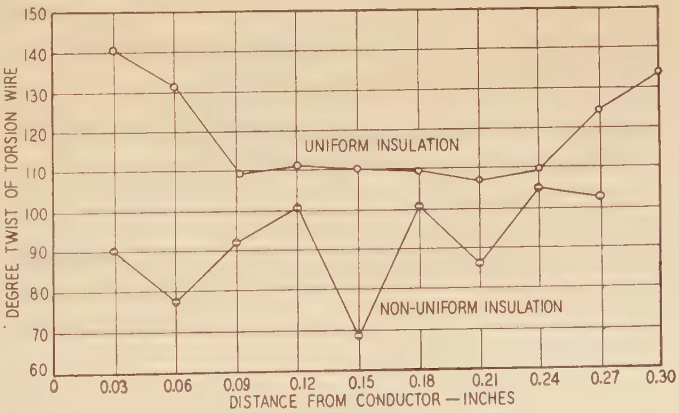


Figure 13. Curves showing radial variation in compactness across insulation wall of cables similar to those shown in figures 4 and 5

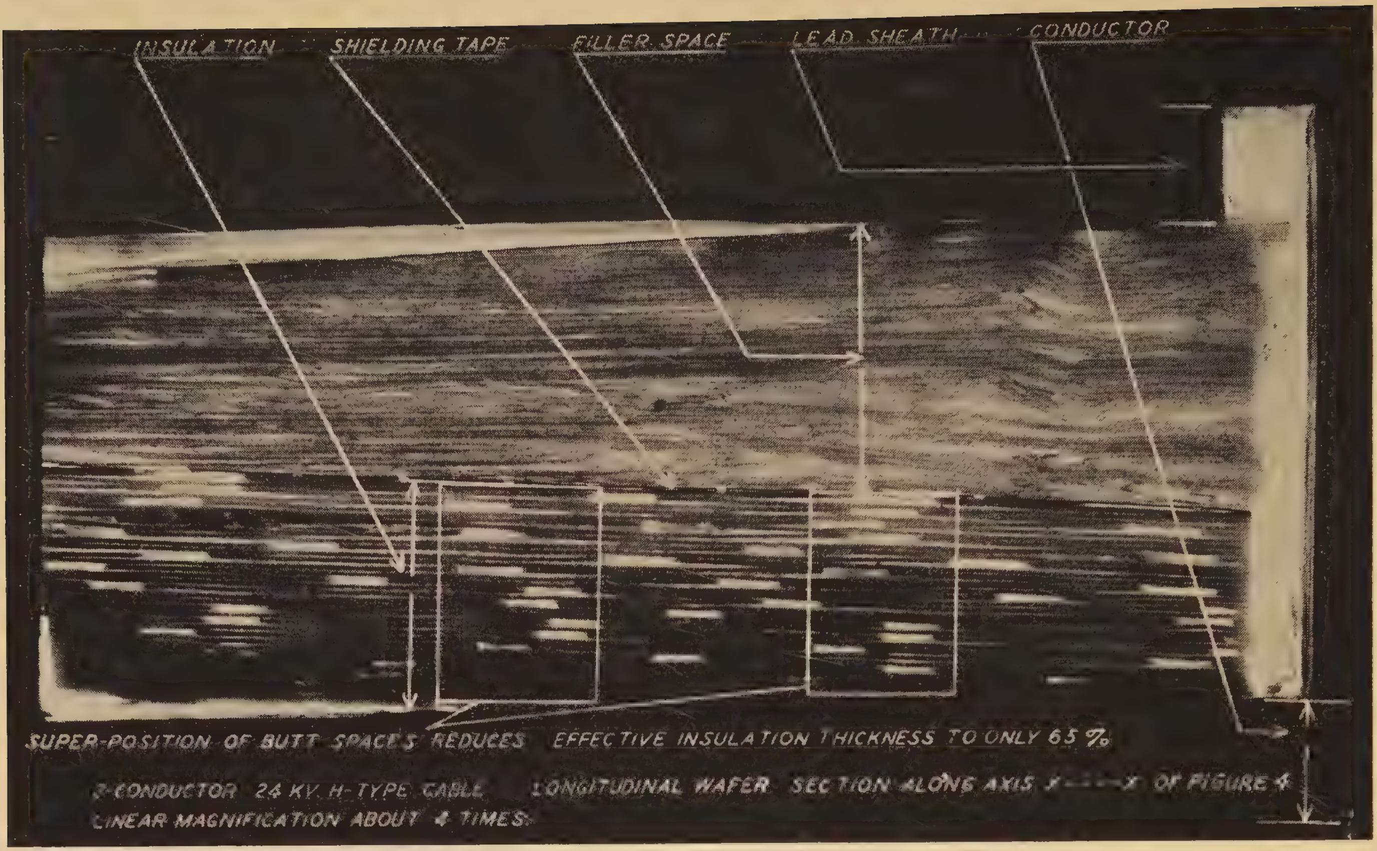

INSULATION
SHIELDING TAPE
FILLER SPACE
LEAD SHEATH
CONDUCTOR
SUPER-POSITION OF BUTT SPACES REDUCES EFFECTIVE INSULATION THICKNESS TO ONLY 65 %
3-CONDUCTOR 24 KV. H-TYPE CABLE LONGITUDINAL WAFER SECTION ALONG AXIS X——X OF FIGURE 4
LINEAR MAGNIFICATION ABOUT 4 TIMES.

Figure 14. Longitudinal wafer taken from plane perpendicular to axis X-X shown in figure 4

other hand, another make of cable which had been subjected to a copper temperature of 45 degrees centigrade during load-cycle aging showed no structural changes whatever in the insulation or sheath, and even 55 degrees centigrade load cycles appeared to have only a slight effect, if any, on the layer structure. The tentative conclusion from waferizing over 15 cables which had received load-cycle treatment is that up to 55 degrees centigrade or over, either the oil is so fluid that it flows outward and inward with the heating and cooling cycles causing no distortion, or what is more probable, that up to some critical temperature above 55 degrees centigrade the oil and paper insulation expand as a unit, and that above this temperature differential expansion of the oil occurs.[6]

In correlating load-cycle with service aging, D. W. Roper[7] showed that the cable which performed poorest in service performed poorest on the load cycle. A wafer of the cable after the load-cycle test (figure 12) shows a very loose layer structure with an abundance of interlayer spaces. The small rectangular spaces, one of which is indicated by an arrow, must not be confused with voids; these represent butt spaces which are visible whenever the thickness of the wafer is less than the axial width of a butt space.

Load cycles in service also cause longitudinal movements which may affect the cable structure, but the effects of these on the structure have not been studied.[8]

In waferizing cable from service it is usually sufficient to prepare only one wafer from a cable length, since this is generally representative. For example, wafers of one make of cable over the past seven years reveal characteristic nonuniformities. On the other hand, where it is known that local hot-spots are present, it is necessary to waferize at more frequent intervals.

Correlation With Mechanical Tests

The results of the mechanical tests support and supplement the results of waferizing. The torsion method is particularly valuable. When applied to the sector shoulders of the insulation of cables similar to those shown in figures 4 and 5, the torsion test gave results which, when plotted against distance from conductor, gave the radial curves shown in figure 13. The test is sufficiently sensitive to show the decrease in compactness of insulation after severe load cycles.

The penetrometer test is chiefly useful for evaluating compactness of filler spaces, but it also differentiates between compact and loose insulation. The results of tests on the cables mentioned above were as shown in table I.

The push-out test gave pressure readings of 13 and 4 pounds, respectively, for the compact and loose insulations, indicating the sensitiveness of this criterion for compactness. The types of cones which were formed during push-out did not appear to be a reliable measure of compactness.

Longitudinal Wafers

An entirely different set of insulation characteristics is brought out by waferizing longitudinally. Such a wafer for the axis *X-X* of the wafer shown in figure 4 is shown in figure 14. It is immediately obvious that the

Table I. Depth of Penetration (in Millimeters)

	Insulation	Lateral Fillers	Central Fillers
Nonuniform cable	3.9	5.6	11.5
Uniform cable	3.3	4.5	Too soft to measure

Table II

Percentage of Overlay	Amount of Overlay (Inch)	Length of Shortest Leakage Path (Inch)	
		"Zig-Zag"	"Step"
50	0.450	20.2	22.7
40	0.360	20.2	18.2
30	0.270	20.2	13.7
25	0.225	20.2	11.4
20	0.180	20.2	9.2
10	0.090	20.2	4.7

butt spaces, instead of being symmetrically staggered diagonally from conductor to sheath, are arranged somewhat at random, and that in consequence there are two locations where several butt spaces are superimposed along a radius with a corresponding reduction in effective solid insulation thickness. In one case this thickness is reduced by 33 per cent. Moreover, the length of the shortest leakage path from conductor to sheath, believed to be an important factor in breakdown, is greatly reduced at these locations. In addition to revealing flaws and faults in the layer structure the longitudinal wafers therefore provide an ideal method for making measurements for statistical studies of regularity of taping.

Analysis of Taping Theory

A simple and effective method of quantitatively evaluating uniformity of butt-space arrangement has been devised by Mildner and Scott, who were using it in studies of taping machine control at the time one of the authors was visiting their laboratory.[9] It consists of making measurements of the overlay of each tape in the insulation wall and of plotting these values, expressed to the nearest five per cent in percentage of lay, i.e., pitch or axial width of a tape and butt space, against frequency of occurrence in the form of a distribution curve. These values may be obtained with a traveling microscope from a longitudinal wafer. The method when applied to two samples of American cable yielded the distribution curves of figure 15. In the upper curve it is evident that, although a 67–33 overlay was aimed at, the butt-space distribution is not far from random. In the cable of the lower curve, in which a 60–40 overlay was evidently the goal, fairly close control is indicated.

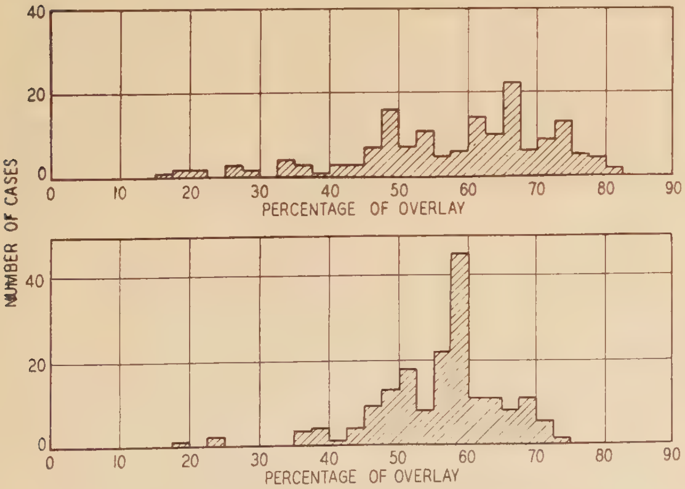
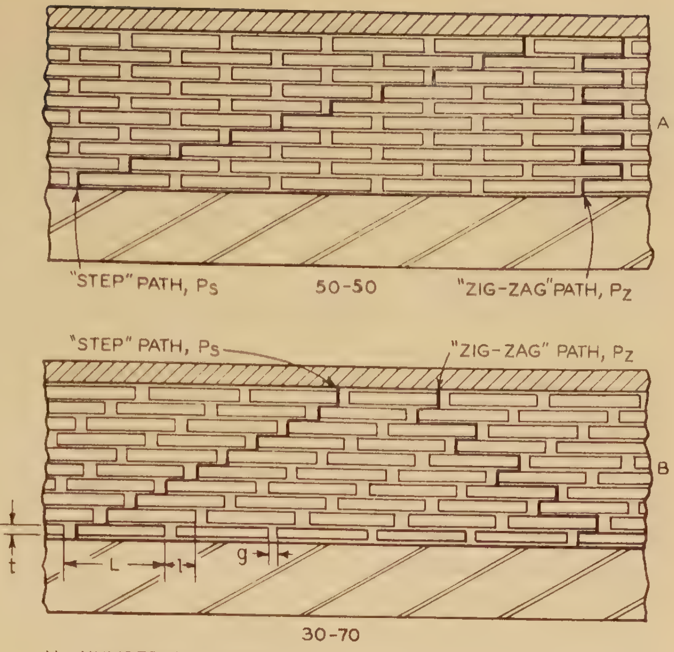


Figure 15. Mildner diagram of butt-space distribution



N = NUMBER OF LAYERS

P_Z (LENGTH OF SHORTEST "ZIG-ZAG" PATH) $= tN + (N-1)\left(\frac{L}{2} - g\right)$

P_S (LENGTH OF SHORTEST "STEP" PATH $= tN + (N-1)l - g$, WHEN $l \geqq g$

Figure 16. Diagram showing effect of various percentages of overlay on minimum insulation thickness and leakage paths

Tape "wander" may also be plotted in the form of Mildner distribution curves.

Influence of Overlay on Effective Thickness and Shortest Leakage Path

The proper choice of overlay is important in producing cable of good quality because it determines the minimum number of butt spaces which may line up across a radius, thus reducing the effective solid insulation thickness, and rendering the cable particularly susceptible to breakdown as a result of transient voltages.[10] It also influences the length of the shortest leakage path, which according to the tracking theory of Robinson[11] may be more important than effective insulation thickness. There are two general types of path from conductor to sheath over the surface of the paper tapes, either of which may be the shortest, depending on the overlay. One is the "zig-zag" type, and the other the "step" type, both of which are shown in diagrams *A* and *B* of figure 16. The length of the "zig-zag" path is independent of overlay, whereas that of the "step" path is almost a direct function thereof. The equations are given on figure 16.

In analyzing cable structure, the length of the step path is of importance, the length of the zig-zag path being fixed for a given width of tape and of butt space. It may be greatly reduced either by tape "wander" and consequent registration, or by poor choice of overlay. For example, in a cable having 51 layers of tape 0.850 inches wide and 0.005 inches thick, and a butt space width of 0.050 inches, the lengths of shortest leakage path for various overlays vary widely as shown by table II.

Relation Between Mechanical and Electrical Characteristics

While it would be unreasonable to seek a relationship between mechanical uniformity and dielectric loss resulting from poorly dried insulation or the use of high-loss materials, yet it is entirely logical to expect a relationship between mechanical uniformity and ionization characteristics. The latter should be true in view of the numerous researches described in the literature showing that ionization in cables takes place in gas films of not inconsiderable dimensions. Further, since ionization is held to be the chief cause of inherent failure, it is reasonable to expect a relationship between mechanical uniformity and life.

IONIZATION

The search for a relationship between ionization factor and imperfections in the cable insulation structure, as made visible by the cross-sectional wafer method, was made comparatively easy by the availability of a number of samples of three-conductor 24-kv cable of known ionization characteristics. These had been saved in a sealed condition from load-cycle aging tests run over a period of years. In addition six samples of single conductor 66-kv cable, also of known electrical characteristics, were very kindly supplied by Mr. H. Halperin of the Commonwealth Edison Company, Chicago, Illinois. Upon waferizing the 66-kv samples, it was found that the best with respect to visible defects in the wafer structure had a maximum ionization factor of minus 0.01 per cent; this cable gave satisfactory results on load cycle and in service. The worst (figure 12) had an ionization factor of 1.15 per cent, the highest of any of the samples; it had a poor load-cycle and service record.[7] In the remaining four samples, with one exception, mechanical characteristics and ionization factor show good agreement.

Out of 18 three-conductor 24-kv cables 17 showed good agreement between ionization factor and number and distribution of voids as determined by visual inspection of the wafers. The relation was especially good for cables of the same make and age. The wafer showing the most uniform insulation had an ionization factor of only 0.08 per cent, whereas in a cable with pronounced imperfections (figure 11) the ionization factor was 3.1 per cent.

The results obtained in this study confirm the belief that there is a relationship between mechanical gaps and imperfections in the insulation, and ionization factor. However, when these gaps are filled with oil, as when the cable is new, the ionization factor may be low. It is only when the oil drains out of these gaps as a result of laying the cable on slopes, or is forced out by the effect of the load cycle, that ionization can occur in them and that the relationship stated above holds true.

In the light of this relationship, the explanation of the observation[12] that two conductors of the three-conductor sector-type cable show a different ionization factor than the third, becomes simple, because as has already been mentioned, two insulated conductors of such a cable are crushed in the cabling process to a different degree from the third.

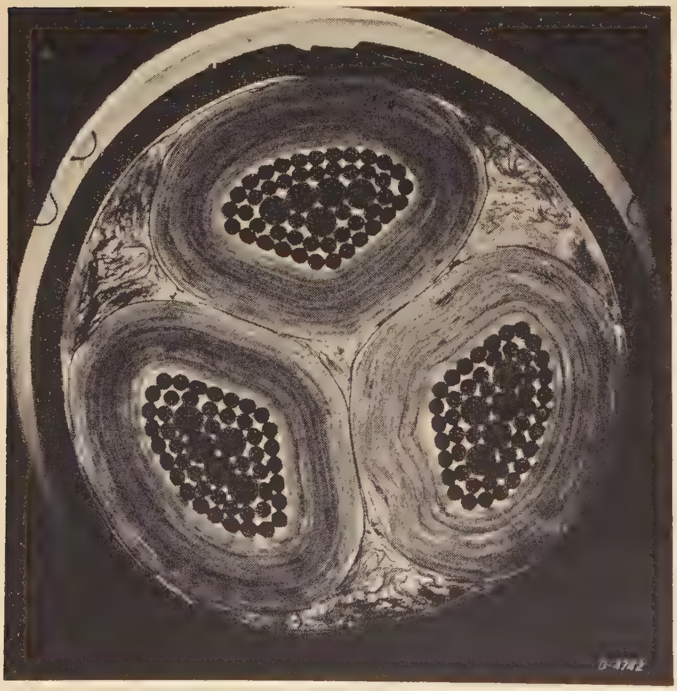


Figure 17. Wafer of three-conductor, 24-kv cable showing wrinkled insulation of conductor which failed on load cycle

LIFE

Since ionization is probably the chief cause of inherent failures, and in view of the relation between ionization and visible voids, it is inevitable that a relation between mechanical characteristics and life should exist. Failures in service in which sufficient evidence remains to permit definite assignment of the cause are not easy to obtain, and some time must necessarily elapse before a complete case can be made. Some evidence is already at hand, however, in the form of life on load-cycle aging and on high-voltage test. The cable represented by the wafer of figure 17 failed on test after only three load-cycles on the conductor on which the wrinkle appears so prominently. When three-conductor sector-type cable is subjected to high-voltage tests at the factory, seven out of ten failures occur in some makes at the insulation of the lagging shoulder, i.e., in the vicinity of the "comet's tail."

Voids in the middle of the insulation wall are thought by Robinson[11] not to be a serious cause of trouble, it being his contention that breakdown starts at the conductor and proceeds slowly through the insulation by a coring and tracking mechanism. Granting the correctness of his theory of breakdown, it must be conceded that the presence of severe ionization in the middle insulation wall would aid in initiating coring at the conductor, since ioniza-

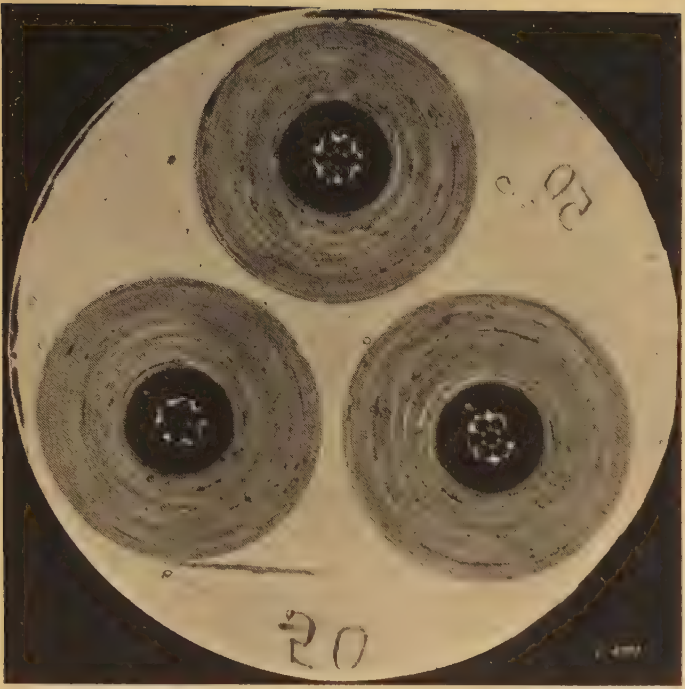


Figure 18a. Wafer of three-conductor, 24-kv joint made by experienced splicer

tion in a void reduces the potential drop across it to very low values, thus increasing the gradient in the rest of the insulation and, in turn, at the conductor. Where voids in different layers are interconnected and form chains of ionized layers, the gradient at the conductor might be very seriously increased. Superimposed on the effect of increased stress resulting from ionization in the middle insulation wall is a high frequency component; Robinson points out the greater ease with which breakdown occurs as the frequency increases.

Tracking along paper surfaces, which is now coming to be accepted as the mechanism of ionization failure after a core has once formed, is believed to be dependent not only on the type of oil used and the stress, but on the radial thickness of the interlayer space and on the extent to which the adjacent layers are pressed together. In other words, tracking is thought to be more difficult in a compact insulation. For these reasons it seems unwise to rule out the effect on life of large gaps and voids at any point throughout the insulation wall.

From the evidence obtained so far there appears to be a good correlation between mechanical uniformity of cable insulation and ionization factor, and, in those cases where ionization is responsible for failure between uniformity and time-to-breakdown in service.

Suggested Uses of Tests for Mechanical Uniformity

Because so little attention appears to have been given to mechanical uniformity of high voltage insulation up to the present time, a wide range of useful applications of the test methods which have been described immediately suggest themselves.[13] These methods should be equally useful to both divisions of the industry.

Among the many uses to which the methods might be put by the utilities, perhaps the most important is that of helping evaluate more precisely the comparative quality of different makes of cable. For this the occasional use of the wafer method is indicated, supplemented by the more frequent use of the torsion and other tests. By waferizing before and after subjecting the cable to severe load-cycles, it should be possible to judge the heat-cycle stability of cables; and indeed, when more data has been accumulated, it may be possible to substitute this and other tests for the tedious and costly load-cycle test. In a similar manner, it may be possible to determine the critical temperature at which the cable structure becomes permanently damaged, that is, to determine maximum safe operating temperatures. Another important use for the test methods, particularly the longitudinal wafer method, should be to analyze the cause of failures in service more satisfactorily. By careful study it will be possible to learn whether present methods of installation of cable cause serious damage to the insulation. In the jointing school the wafer may be used effectively to demonstrate the result of tightly and loosely wound taping on the final structure. (See figure 18.) By pulling from the ground cables of different types and vintages and then waferizing them, a useful educational illuminated display of the history of improvement of cable construction could be produced.

To the manufacturer, the test methods should find their most important use in factory control. Through their continued use, it should be possible to improve both design and the mechanical assembly of cables. The load-cycle stability should now be capable of improvement through selection of oils and papers and adjustment of processes in the light of the results obtainable by the wafer method. Another important problem which should be capable of

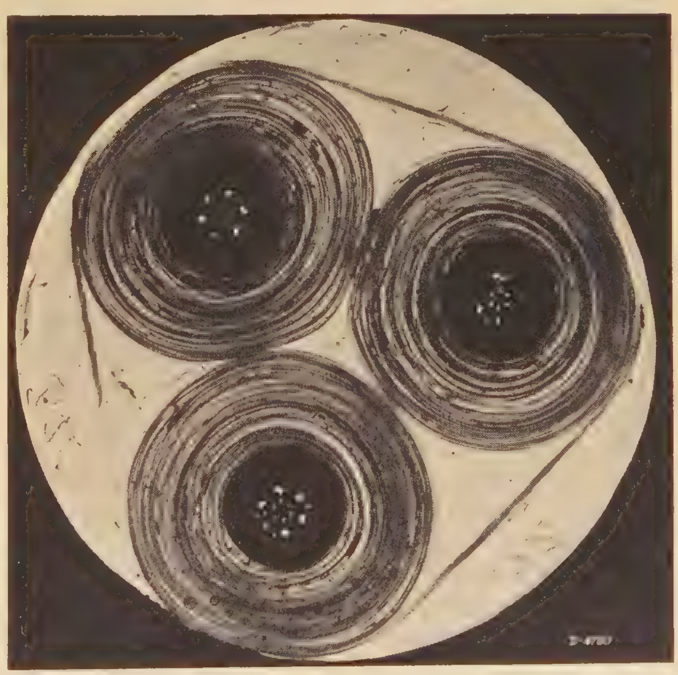


Figure 18b. Wafer of three-conductor, 24-kv joint made by less experienced splicer than the one making the joint shown in figure 18a

solution with these methods is that of the best manner of varying the tape tensions across the radius so as to make an insulation which is compact and which will at the same time satisfactorily pass the specification bending test.

When these improvements have been effected and methods developed of applying paper tapes to the conductor with such precision that the overlay cannot be other than perfect, so that the shortest leakage path must always be at a maximum, and so that it is impossible to have registration and resulting weak spots periodically through portions of the insulation wall, it should be possible radically to reduce insulation thicknesses. In cutting down the insulation wall, once mechanical perfection is possible, the task of the manufacturer is made easier, not harder, because the volume of oil causing expansion troubles is reduced, the radial resistance to oil flow is reduced making return of the oil after the heat cycle more easy, and the thermal resistance is diminished. Reduction of insulation thickness should mean, on the one hand, ability to transmit more power through a congested duct system, and on the other, reduction in cost and a further closing of the gap between economics of underground and overhead construction.

Carried to its logical end, improvement in mechanical uniformity should at some time in the future make possible the use of solid cable at 100 kv or over, without resort to pressure devices to suppress ionization.

Conclusions

The test methods which have been described make it possible to evaluate the mechanical characteristics of cable insulation. They are reliable and suitable for general use. The wafer method is most important because by its use it is possible virtually to see into the insulation structure. The cross-sectional wafer brings out irregularities resulting from taping with variable tension, the use of paper with nonuniform shrinkage characteristics, and distortion of the insulation of three-conductor sector cable as a result of cabling. The longitudinal wafer reveals the percentage of overlay used in the taping, and the precision with which the tapes were applied. The torsion method is simple, rapid, and sufficiently sensitive to make possible comparisons of radial variations in compactness across the insulation wall of new cable, and the evaluation of changes in compactness as a result of load-cycles or of bending. The penetrometer test is useful in measuring compactness of filler spaces. The push-out test furnishes a quick means of detecting especially loose insulation.

The application of the test methods to new and used cable shows most modern cable still to be mechanically imperfect. Wide differences may be found in average compactness of the insulation wall, and in the manner of varying the compactness across it.

Granted the use of low-loss paper and oil, and reasonably thorough drying, degassing, and impregnation, mechanical uniformity of cable as manufactured is the foundation of cable quality for it determines in large degree the ionization characteristics, and probably accounts for a large proportion of inherent failures.

The study of mechanical uniformity throws open the door to improvement of high voltage cable in several directions. Improved load-cycle stability may now be expected, and ultimately, when ways can be found of applying taping with absolute precision, radical reductions in insulation thickness should be possible. Perhaps it will be practicable to raise the upper voltage limits for solid-type cable so that it may compete with the more complicated pressure types. Possibly improvement of mechanical uniformity is the last major step to be taken to bring oil-impregnated paper cable to the same level of efficiency and reliability as other types of electrical equipment.

Acknowledgment

The work described forms part of a comprehensive research on high-voltage cable insulation by The Detroit Edison Company, under the direction of C. F. Hirshfeld. The authors wish to express their appreciation to the entire laboratory staff who freely contributed to this work in suggestions and help; and to the cable manufacturers, who through throwing open their plants and through frank discussion, made possible interpretation of cable wafers in terms of design and manufacturing processes. They are also indebted to Professor C. S. Schoepfle of the University of Michigan for preparing the densitometer curve, and for his advice and encouragement.

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The Current-Carrying Capacity of Rubber-Insulated Conductors

By S. J. ROSCH
ASSOCIATE AIEE

Introduction

THE INVESTIGATION described in this paper was initiated in 1931 by The Rubber Insulated Wire and Cable Section of The National Electrical Manufacturers' Association (NEMA), for the purpose of determining the current-carrying capacities of rubber-insulated wires and cables installed in buildings. The reasons for this investigation were as follows:

(*a*). Rubber-covered wires and cables had undergone considerable changes in design and chemical composition during the preceding ten years, without any advantage being reflected in increased current-carrying capacity. On the other hand, many changes in building materials and methods during a number of years may have had an adverse effect on the heat-dissipating condition of wires and cables.

(*b*). The table of permissible current ratings for rubber-insulated wires and cables, as printed in the National Electrical Code, was presumably based on a maximum safe operating temperature of 49 degrees centigrade (120.2 degrees Fahrenheit), although it refers to this temperature as the "ambient" temperature. The standardization rules of the AIEE specify a maximum safe operating temperature for rubber-insulated conductors of $(60\text{-}E/4)$ degrees centigrade, which in the case of 600 volts operation would correspond approximately to 60 degrees centigrade (140 degrees Fahrenheit). Since the AIEE is represented in the formation of the National Electrical Code, it would appear as though the rules promulgated by these respective organizations were in conflict.

(*c*). If the AIEE interpretation of ambient temperature were applied literally to the Code ratings, the ultimate temperature of some of the conductors when loaded according to these ratings, would approach close to 70 degrees centigrade (158 degrees Fahrenheit).

(*d*). Although it had been known for some time that grouping of the conductors results in the lowering of the allowable current carrying capacity, there was no indication in the Code of the reduction to be expected, for example, in a three-conductor as contrasted with a single-conductor cable.

(*e*). As a result of misinterpretation of the current-carrying capacity table in the Code, frequent cases of trouble had been experienced in the operation of rubber-covered cables, without any apparent violation of the Code having been committed in the wiring layout or installation. A typical example of one of these cases may be seen in figure 1.

This represents two samples of rubber insulation taken from a 400-foot length of single-conductor 500,000-circular-mil, taped and weatherproof braided cable, which had been installed in the basement of a public building. Of the entire run, about 17 feet passed through the boiler room where the ambient temperature averaged between 102 and 110 degrees Fahrenheit (38.9 and 43.3 degrees centigrade), while the balance of the run outside of the boiler room had an average ambient temperature of 70 degrees Fahrenheit (21.1 degrees centigrade). The installation consisted of three single conductors in conduit with 380 amperes per phase and had been in operation for about two years before being withdrawn due to alterations in the wiring layout. It was then that the conditions as indicated in figure 1 were noted. The upper portion of figure 1 shows the appearance of the insulation taken from the cooler section of the cable, while the lower indicates the appearance of a section taken from the run installed in the boiler room.

Obviously, the hot-spot condition should have been provided with a larger conductor size so as to reduce the rise in temperature above the ambient, so that the maximum temperature rise would not exceed the maximum permissible insulation temperature of 122 degrees Fahrenheit (50 degrees centigrade), as provided by the Code. This installation was carried out in accordance with the then existing Code rules.

(*f*). Although the table of allowable current-carrying capacity appearing in the Code had been reproduced in various engineering handbooks, trade publications, catalogs, textbooks and other sources of authoritative engineering information for more than 30 years, none of these publications ever gave any indication of the basis used in the formation of this table as in the case of current-carrying capacity tables given for impregnated paper insulated cables.[1]

(*g*). Periodically, various engineering publications would contain articles dealing with the subject of current-carrying capacity of rubber insulated wires and cables, but giving permissible current loadings at variance with those found in the code. These would not only be confined to technical articles, but would also appear in the form of standards to be observed in a given territory.[2]

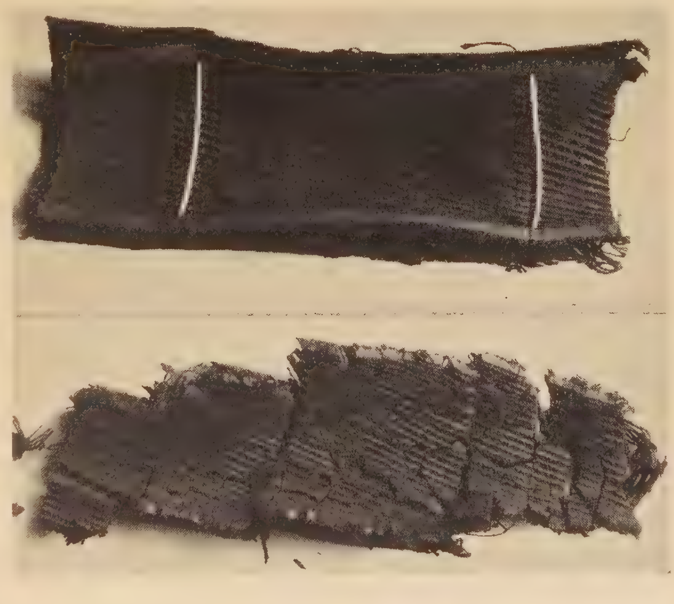

Figure 1. Effect of hot-spot temperature on rubber insulation

Plan of Investigation

After a thorough study, the committee consisting of Messrs. E. D. Youmans, G. W. Zink, and the author as chairman, formulated the following program.

Paper number 37-155 recommended by the AIEE committees on power transmission and distribution and research, and presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted November 3, 1937; made available for preprinting January 6, 1938.

S. J. Rosch is manager of insulated products development for the Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

1. For all numbered references, see list at end of paper.

Table I. Summary of Cable Ratings

	Current-Carrying Capacity (Amperes)																				
	(a)	(b)	(c)	(d)	(e)	(f)		(g)	(h)	(i)				(j)						(k)	(l)
	1889	1890	1894	1894	1896	1903		1906	1912	1913				1934						1931–37	1895
						IEE Wiring Rules Ambient				Dushman				IEE Wiring Rules							
Conductor Size (Awg or Circular Mils)	Kennelly	Fisher	Insurance Rules	National Electrical Code	AIEE & National Elec. Code	High	Normal	Fisher	R. H. Rice	Temperature Rise °C 30	20	10	G-E Bulletin	2–1/Cond Cables D-C	A-C	4–1/C or 1–3/C	6–1/C or 1–4/C	8–1/C or 2–3/C	10–1/C or 2–4/C	National Electrical Code	Puffer: Amperes to Produce Smoking
18		4.5			3			4.5												3	
16		6.4			6			6.4								5		5		6	
14	25	9.5	10	13	12			9.1								10		8		15	48
12	33	13.5	15	17	17			12.9								15		12		20	65
10	46	19.1	20	23	24			18.3		41	34	24	20	24	24	19	17		14	25	87
8	58	27.0	25	29	33			31.3						37	37	30	26		22	35	127
6	78	38.2	35	39	46			44.3		76	63	45	50	46	46	37	32		28	50	155
5	90	45.4	45	45	54			52.5													178
4	104	54.1	50	52	65			62.7		105	88	63	75	53	53	42	37		32	70	207
3	120	64.4	60	60	76			74.4												80	237
2	144	76.6	70	72	90	42	64	86.6												90	273
1	172	91.1	85	86	107			105.4						83	83	66	58		50	100	319
0	206	108.5	100	103	127			127.8		199	166	119	165							125	372
00	246	129.0	120	123	150	71	113	151.7						118	118	94	83		71	150	438
000	298	153.5	145	149	177	84	136	180.8												175	519
0000	360	182.7	175	180	210	96	158	215.2												225	630
200,000					200									152	152	122	106		91	200	
300,000		237.0			270	145	241	281						214	214	171	150			275	
400,000		294.0			330	166	279	349												325	
500,000		348.0			390	208	354	413	500	572	476	342	550	288	288	230				400	
600,000					450	248	425	474												450	
700,000					500			532												500	
800,000					550			587						384	366					550	
900,000					600			641												600	
1,000,000					650			694	800	925	769	554	900							650	
1,100,000					690	390	688	746						512	463					690	
1,200,000					730			797												730	
1,300,000					770	424	750	846												770	
1,400,000					810			894						595	520					810	
1,500,000					850			942												850	
1,600,000					890			989												890	
1,700,000					930			1,035												930	
1,800,000					970			1,080												970	
1,900,000					1,010			1,125												1,010	
2,000,000					1,050			1,169		1,501	1,247	898	1,400							1,050	

1. Investigate the historical data in connection with the Code values of permissible current carrying capacities for rubber insulated conductors, as well as the work of other investigators in this field.

2. Determine the factors affecting current carrying capacity under various installation conditions of wires and cables in buildings.

3. Determine the maximum continuous safe operating temperature of Code-grade rubber insulation.

4. Determine the thermal surface resistivity of the customary outer coverings of building wires and cables, also similar factors for metal conduit.

5. Set up the necessary formulae for the calculation of allowable current carrying capacities for building sizes of wires and cables under the various conditions of installation.

Historical Data

Space does not permit the inclusion of all of the historical data, but the following references will serve as an indication of the development of the present Code values of current carrying capacity, as well as some of the independent ratings that appeared during various periods. To facilitate the study of this development the various ratings have been abstracted from their respective sources and set up in comparative form in table I.

In 1849, John Müller[3] reached the conclusion that for a bare conductor, the temperature rise varies as the 1.5 power of the current flowing through the conductor.

In 1881, Lord Kelvin, speaking before the British Association for the Advancement of Science,[4] first enunciated the famous law associated with his name "that the most economical size of conductor is found by placing the cost of the annual conductor loss equal to the annual charge for maintenance, depreciation and interest on the money invested."

In 1883, Thomas Gray[5] found that a current density of 134 amperes per square centimeter was a representative figure for copper conductors from an economic point of view. However, he went further than Lord Kelvin by recognizing the need of voltage regulation and limiting the current so as not to cause overheating.

In 1884, J. T. Bottomley[6] presented results of an investigation, the primary purpose of which was to determine the ultimate steady state temperature of electric light conductors under a given loading, as well as their thermal surface emissivity, basing his results on conductors of comparatively small diameter and various insulating coverings. His was probably the first effort at recording a table of materials in the order of their heat emissivities. He also showed that under a given loading, insulated conductors did not run hotter than bare conductors, but on the contrary, with higher current densities had a tendency to run cooler. This had previously been shown to be theoretically possible according to an editorial by Sir William Thomson (Lord Kelvin),[7] and was based on the fact that the thermal resistance of the insulating coverings was offset by the increased dissipating surface provided by the increase in diameter.

In 1884, Prof. George Forbes[8] presented a paper which was destined to have a very important bearing on the formation of our present Code values. In this paper he concerned himself with the heating effects produced by the current ratings then in effect, severely criticizing the British Fire Risks Committee for their arbitrary practice in 1882 in setting up a limit of 1,000 amperes per square inch of conductor cross section, pointing out that whereas, this may be a safe limit for the smaller wires, it might produce dangerous overheating in the case of larger conductors. He also claimed that the square of the current is proportional to the cube of the conductor diameter, adding however, that in the case of small conductors, convection is of greater consequence than radiation, his law is only applicable to the larger conductors where radiation is the major method of heat dissipation.

In 1889, Dr. A. E. Kennelly[9] published a series of articles based on an original investigation conducted at the Edison Laboratory in Orange, New Jersey. This investigation was undertaken on behalf of some fire insurance companies to determine the heating produced by certain current loadings and this afforded him an opportunity to verify Professor Forbes' findings. In his published data, Doctor Kennelly gave a table of current ratings (see table I, column *a*) based on an ambient temperature of 75 degrees Fahrenheit (23.9 degrees centigrade) and an allowable temperature rise of 75 degrees Fahrenheit (41.6 degrees centigrade), or an ultimate temperature of 150 degrees Fahrenheit (65.6 degrees centigrade). The reason for setting the upper temperature limit at 150 degrees Fahrenheit (65.6 degrees centigrade) was that Doctor Kennelly felt this to be the danger point for rubber insulation. We shall see later how this table became the basis of our present Code ratings.

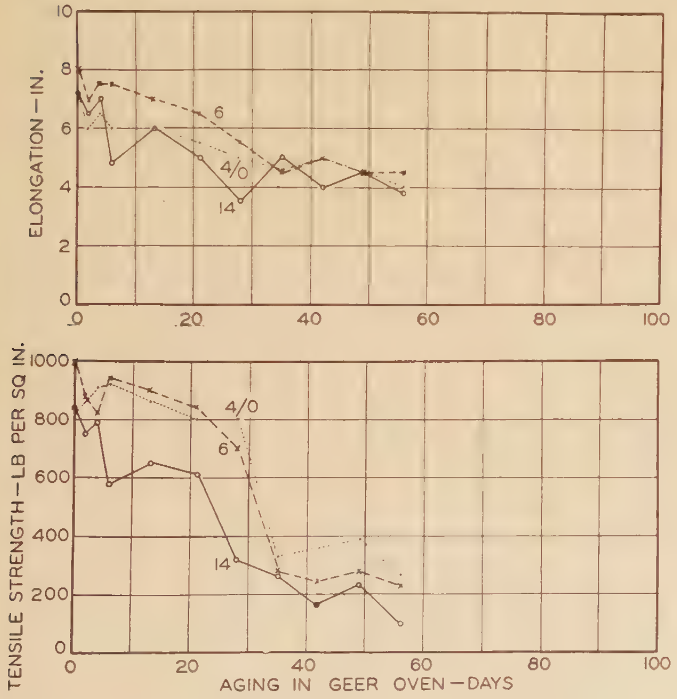

Figure 2. Effect of aging at 60 degrees centigrade, Code-grade rubber insulation, manufacture A

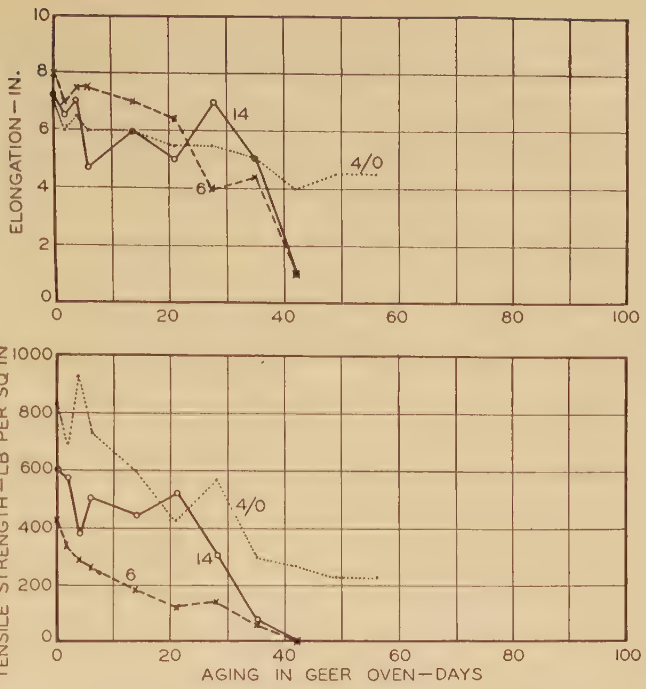

Figure 3. Effect of aging at 60 degrees centigrade, Code-grade rubber insulation, manufacture B

Doctor Kennelly's investigation included three different installation conditions.

Insulated copper conductors installed in wooden paneling to represent house wiring.

Bare and insulated copper conductors installed outdoors on poles.

Bare copper conductors suspended indoors to represent an installation in a central station.

In 1890, H. W. Fisher[10] published a table of current ratings which were very widely used (see table I, column *b*). This table was based on the results of a series of original researches.

In 1894, the insurance rules[11] prevalent in the country prescribed a table of maximum current ratings (see table I, column *c*). These were apparently based on 50 per cent of the values proposed by Kennelly, but rounded off to the nearest 5 amperes.

In 1894, the National Electrical Code[11] (then known as the Underwriters' National Electrical Association) also published a table of similar ratings, but based on an exact 50 per cent of Kennelly's values (see table I, column *d*).

On January 10, 1895[11] this same body proposed that their 1894 values be increased 25 per cent for concealed installations, such as in paneling, and 75 per cent for open wiring, such as cleating or knob and tube wiring. This was strongly protested at a meeting of the AIEE as being arbitrary and tending to be unsafe.

In 1895, Professor William L. Puffer[11] offered the results of some original work at Massachusetts Institute of Technology in the form of a table of current values which would cause the insulations then available to begin smoking. Tests on 75 samples of wire indicated that the results could be expressed by the formula

$$I = 1{,}610d^{1.28}$$

where

I = current in amperes to produce smoking

and

d = conductor diameter in inches

These values are reproduced in table I, column 1, as a matter of interest.

So many tables of current ratings began to be issued that finally on March 19, 1896,[12] a committee consisting of the leading engineering societies and insurance companies, finally agreed on a table of current ratings, taking approximately 60 per cent of Kennelly's original values (table I, column *a*) and stating that with an ambient of 75 degrees Fahrenheit (23.9 degrees centigrade), these new current ratings would yield a temperature rise of 29 degrees Fahrenheit (16.1 degrees centigrade) above the temperature of the surrounding air. The value of 75 degrees Fahrenheit (23.9 degrees centigrade) was chosen as the average indoor temperature. The values adopted are given in table I, column *e*, and it is to be noted that "these currents are specified for rubber-covered wires to prevent gradual deterioration of the insulation by the heat of the wires, but not from fear of igniting the insulation. The question of drop is not taken into consideration in the above table."

The reason assigned for adopting only 60 per cent of Kennelly's original values, was that the margin of 40 per cent was to allow for the inevitable increase in current, such as that produced by the changing from one size lamp to those of a larger candlepower, the adding of more lamps to a circuit, the overloading of a motor, etc.

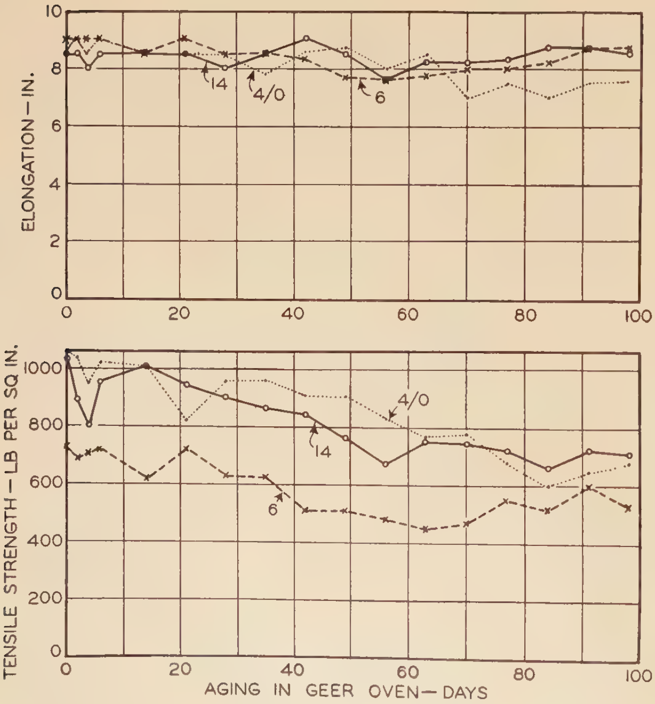

Figure 4. Effect of aging at 50 degrees centigrade, Code-grade rubber insulation, manufacture A

In 1903, the Institution of Electrical Engineers (British),[13] issued a set of wiring rules in which they recognized the maximum operating temperature of rubber-insulated conductors as 130 degrees Fahrenheit (54.5 degrees centigrade). They also set up two ratings, one for locations of high ambients and the other for ordinary conditions. In view of the difference in the British wire gauge, table I, column *f*, gives excerpts from these rules in terms of the nearest American wire gauge (Awg.). It is interesting to note that these ratings were established even though Doctor Kennelly's findings had already been reported and favorably commented upon in the English technical press.

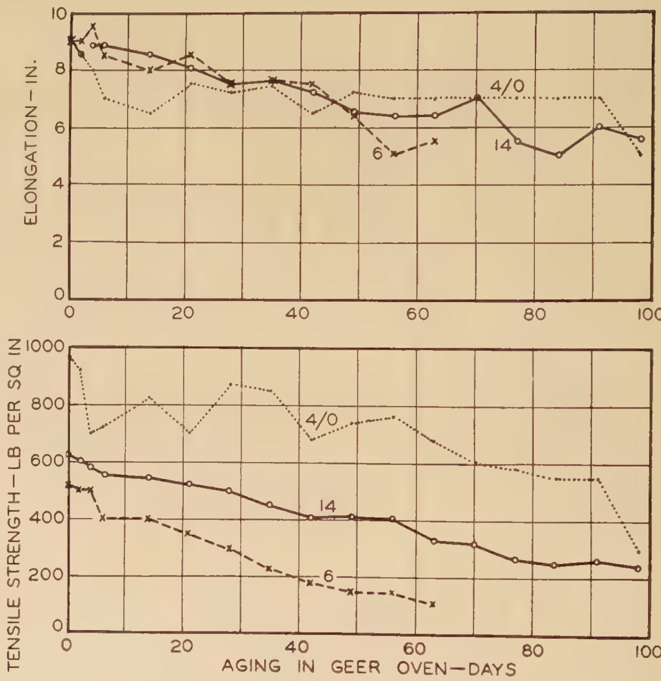

Figure 5. Effect of aging at 50 degrees centigrade, Code-grade rubber insulation, manufacture B

In 1906, H. W. Fisher[14] issued a new set of current ratings for rubber-insulated wires and cables based on Doctor Kennelly's original findings for insulated conductors in panels. These values (table I, column *g*) differed considerably from those adopted by the National Electrical Code[12] in 1896, being considerably greater in value for sizes 8 Awg. and larger. The cable handbook in which they were issued received a very wide distribution throughout the country, being used as a recognized reference text in several engineering schools.

In 1910, Doctor Alexander Russell[15] showed that the temperature rise varied as the 1.25 power of the current flowing through a conductor.

In 1911, Messrs. S. W. Melsom and H. C. Booth[16] presented their classical paper before the IEE, giving the results of a two-year investigation conducted at the National Physical Laboratory at the request of the IEE wiring rules committee. The object of the investigation was to determine the temperature rise as well as the current density for a given temperature rise in rubber- and paper-insulated cables of various sizes and with different types of coverings. In the case of the rubber-insulated conductors, the sizes were confined to those ordinarily encountered in interior wiring. This was the first scientifically conducted experiment, the study actually taking into account observations made under different conditions of installation.

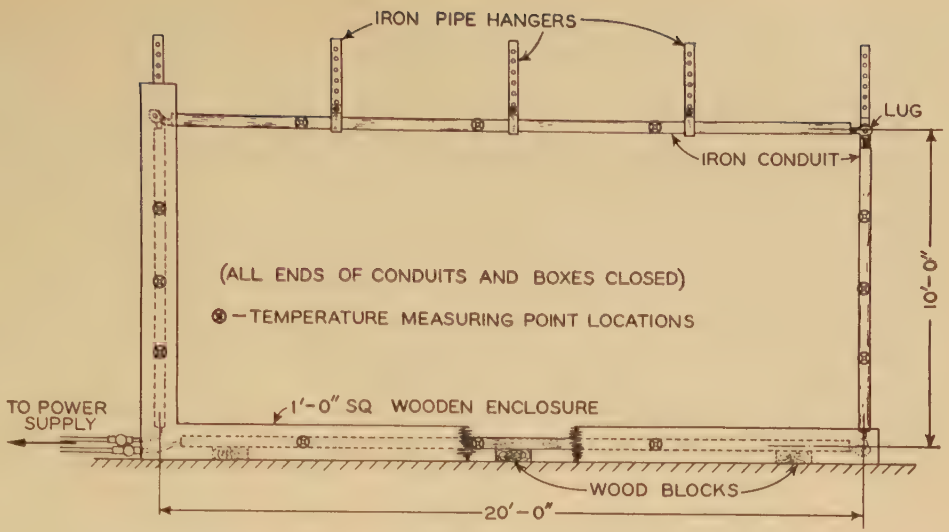
IRON PIPE HANGERS
LUG
IRON CONDUIT
(ALL ENDS OF CONDUITS AND BOXES CLOSED)
⊗ — TEMPERATURE MEASURING POINT LOCATIONS
10′-0″
TO POWER SUPPLY
1′-0″ SQ WOODEN ENCLOSURE
WOOD BLOCKS
20′-0″

Figure 6. Test setup

The authors were interested in the current densities necessary to produce two different values of temperature rise, namely, 20 and 30 degrees Fahrenheit (11.1 and 16.7 degrees centigrade), respectively. Their findings indicated that this data could be expressed by the general formula

$$i = K\left(\frac{D}{S}\right)^n$$

where

i = current density in amperes per square inch
K = a constant varying with each condition
D = outer diameter of completed cable in inches
S = area of copper conductor in square inches
n = an exponent varying with installation conditions

the actual values being found in table II.

The authors also investigated the effects of higher, but intermittent ratings, necessary to produce a given temperature rise.

In 1912, R. H. Rice in discussing a paper by C. T. Mosman[2] gave some of the current ratings for rubber-covered conductors as permitted by the Board of Supervising Engineers of Chicago Traction (see table I, column *h*).

In 1913, Doctor S. Dushman[17] presented a table of current ratings for different values of temperature rise, at the same time drawing a comparison between these and corresponding values published by the General Electric Company for the respective conductor sizes (see table I, column *i*).

Table II. Current-Density Factors—Melsom and Booth

Type of Cable	Temperature Rise of	
	20°F(11.1°C)	30°F(16.7°C)
Rubber-insulated and braided in air..	$i = 364\left(\frac{D}{S}\right)^{0.616}$	$i = 457\left(\frac{D}{S}\right)^{0.616}$
Rubber-insulated and braided in moulding....................	$i = 309\left(\frac{D}{S}\right)^{0.66}$	$i = 358\left(\frac{D}{S}\right)^{0.66}$

Table I, also contains ratings taken from the latest standards of the IEE, as well as the 1931 (same as 1937) ratings given in the National Electrical Code. A study of this tabulation not only reveals the inconsistencies between the various ratings, but that the present Code values are practically the same as adopted in 1896, the difference being that in the present table the values have been expressed to the nearest five amperes.

Factors Affecting Current-Carrying Capacity

The fundamental formula for the current-carrying capacity of a single-conductor rubber-insulated braided cable in conduit is

$$I = \sqrt{\frac{T_0 - T_a}{R_{cu}R_{th}}} \text{ amperes}$$

wherein

T_0 = maximum safe operating temperature of insulation, in degrees centigrade
T_a = ambient temperature, in degrees centigrade
R_{cu} = effective conductor resistance, in ohms per foot
R_{th} = thermal resistance of path from conductor to ambient air, in thermal ohms per foot of cable.

$$R_{th} = 0.00522\left(\rho \log_e \frac{d_1}{d} + \rho_1 \log_e \frac{D}{d_1}\right) + \frac{0.00411B_b}{D} + \frac{0.00411B_c}{D_c}$$

wherein

d = diameter over copper conductor, in inches
d_1 = diameter over insulation, in inches
D = over-all diameter of cable, in inches
D_c = over-all diameter of conduit, in inches
ρ = thermal resistivity of insulation, degrees centigrade per watt per centimeter cube
ρ_1 = thermal resistivity of braid, degrees centigrade per watt per centimeter cube
B_b = thermal surface resistivity of braid, degrees centigrade per watt per centimeter square
B_c = thermal surface resistivity of conduit, degrees centigrade per watt per centimeter square

Examination of the various factors which make up I, shows that the values of T_0, R_{cu}, and R_{th} are the unknowns. Analyzing R_{th}, we find that the industry has been using the following values: $\rho = 500^{18}$; $\rho_1 = 300^{19}$

and B_b = 1,000 to 1,200.[1] In applying these values in the formula for R_{th}, it is found that the thermal resistance of insulation and braid forms only one-fifth to one-tenth of the resistance of the entire thermal path. Therefore, a comparatively large error in ρ and ρ_1 will result in a minor error in current-carrying capacity computation. However, the values of B_b and B_c must be known within closer limits, because any appreciable error in the values of thermal surface resistivity will have a considerable effect on the ultimate current-carrying capacity rating of a given cable.

The industry has been using a value of 1,200 for thermal surface resistivity. This value was based on measurements conducted on cables having an over-all diameter of two inches and larger and was assumed to cover the entire range of diameters. Calculations, as well as experimental determination of the current necessary to produce a given permissible temperature rise on some small conductors, definitely indicated that the value of 1,200 was in error and, consequently, it became necessary to determine the actual thermal surface-resistivity values.

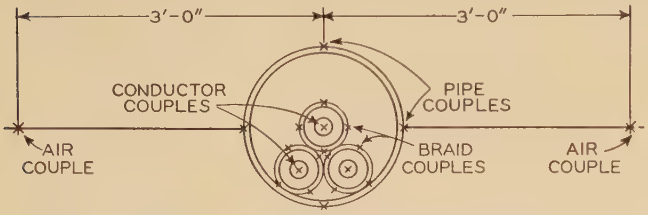

Figure 7. Location of Thermocouples

Number 12 Awg—2 couples on braid
Number 4/0 & 2 Awg—3 couples on braid
500 MCM—4 couples on braid

In addition to determining the values of thermal surface resistivity of cable coverings and conduits, it was also felt necessary to determine the effect of the following variables:

(*a*). Effect of number of conductors in conduit.

(*b*). Nature of outer covering of cable, whether braided or lead covered.

(*c*). The effect of color of outer coverings and conduits, whether black or white.

(*d*). The effect of installation in air or in conduit, concealed or exposed, vertically or horizontally.

All of these factors were taken into consideration as will be shown elsewhere in the paper.

Determination of Maximum Operating Temperature of Code-Grade Rubber Insulation

It has already been pointed out that an apparent conflict exists between the maximum permissible temperatures specified by the Code and those contained in the AIEE–ASA standards, the former calling for a maximum of 49 degrees centigrade, while the latter specifies (60-E/4) degrees centigrade. It was therefore decided to first investigate the behavior of this type of insulation at 60 degrees centigrade.

In order to have the results truly representative, 100-foot coils of number 14 Awg with three-sixty-fourth-inch wall, number 6 Awg with four-sixty-fourth-inch wall, and number 4/0 Awg with five-sixty-fourth-inch wall of Code-grade rubber insulation, finished with a single-moistureproofed braid, a double-moistureproofed braid, and a rubberized tape and moistureproofed braid, respectively, were obtained from nine different cable manufacturers. These coils were cut into one-foot lengths, each length being carefully tagged for proper identification and in that condition, grouped into bundles. Each bundle contained 27 one-foot lengths of wire representing three different sizes contributed by nine manufacturers.

Approximately 40 of these bundles were placed in an oven, containing air in circulation, at a temperature of 60 degrees centigrade ± 0.5 degrees centigrade. The outer coverings were not removed from any of the samples during their stay in the oven. One group of samples which was not subjected to heating, was tested for physical properties and the values obtained were considered the initial values for both tensile strength and elongation.

Table III. Thermal Surface Resistivity B_b (Braided Cables in Air)

Conductor Size (Awg or Mcm)	Over-All Diameter of Cable (Inches)	Thermal Surface Resistivity Bb (Degrees Centigrade per Watt per Centimeter Square)
12	0.216	.530
2	0.518	.611
4/0	0.784	.712
500	1.100	.750
1,000	1.500	.818

During the first week, tests were conducted after two, four, and six days, respectively, of heating in the oven. Thereafter these tests were conducted at the end of each week. When the time for testing would arrive, an entire bundle would be removed from the oven and allowed to cool for 24 hours to room temperature, after which the samples were tested for both tensile and elongation.

Figures 2 and 3 are typical curves of the behavior of the different insulations. In these curves the actual values of tensile and elongation were plotted against time of exposure to 60 degrees centigrade and the trend in the deterioration noted. It was expected that some deterioration would be experienced during the progress of the investigation, but that if the insulation was capable of operating continuously at 60 degrees centigrade, the physical properties would gradually level off to a constant value with time of exposure. Reference to these curves, as well as to the actual results obtained, indicates that at the end of the ninth week of exposure to 60 degrees centigrade, the insulation had deteriorated to such a point that it was impossible for it to be removed from the conductor. Some insulations had become plastic and very soft, while others had hardened and become brittle. It was, therefore concluded that 60 degrees centigrade was too high for the permissible operating temperature of Code-grade insulation.

It was next decided to carry on a similar investigation at 50 degrees centigrade. The procedure was carried out identically as in the previous investigation except that this time two additional cable manufacturers contributed similar samples. Therefore, each bundle now contained 33 different wire samples.

Figures 4 and 5 are representative of the typical behavior of the insulation at 50 degrees centigrade. The materials for figures 2 and 4 were supplied by manufacturer *A* while those in figures 3 and 5 were supplied by manufacturer *B*. It is interesting to note that after approximately 50 days of heating at 50 degrees centigrade, the physical properties began to level off and remained fairly constant thereafter. After the data shown for an elapsed period of 98 days had been secured, as a matter of interest, tests were conducted for 133 days with the values showing a practically constant trend. As a result of this investigation, it was decided that Code-grade insulation could be operated continuously at 50 degrees centigrade.

Before concluding this section of the paper, it might be of interest to note that, other than the experiments conducted by Professor Puffer[11] to determine the values of current at which insulation begins to smoke, there is no published account of any work having been performed in this country to determine the maximum permissible operating temperature of Code-grade insulation.

Attention should be called, however, to some tests conducted by the Union des Syndicats de L'Eléctricité for the Paris City Council.[20] In the latter investigation, five French cable manufacturers contributed a total of 68 samples of rubber covered wire and cable and tests similar in nature to those described in our investigation were carried on to determine the maximum permissible safe operating temperature of rubber insulation. As a result of their findings a decision was reached that the maximum permissible operating temperature at the surface of the conductor in a rubber insulated cable should not exceed 40 degrees centigrade (104 degrees Fahrenheit).

The current ratings contained in the IEE wiring rules[21] are based on a maximum permissible operating temperature of 120 degrees Fahrenheit (48.9 degrees centigrade) for rubber-insulated wires and cables. This is based on an ambient of 100 degrees Fahrenheit (37.7 degrees centigrade) and a maximum temperature rise of 20 degrees Fahrenheit (11.1 degrees centigrade).

The maximum permissible operating temperature for rubber covered wires used in Japan[22] is 55 degrees centigrade (131 degrees Fahrenheit) and is based on an ambient of 40 degrees centigrade (104 degrees Fahrenheit) with a maximum temperature rise of 15 degrees centigrade (27 degrees Fahrenheit).

Determination of Thermal Surface Resistivity of Cable Coverings and Conduits

PREPARATION OF TEST SPECIMENS AND EQUIPMENT

The cables used in this part of the investigation consisted of the following:

Number 12 Awg—three-sixty-fourths-inch wall of rubber, black finished braid

Number 12 Awg—three-sixty-fourths-inch wall of rubber, white finished braid

Number 2 Awg—fouri-sxty-fourths-inch wall of rubber, rubberized tape and black finished braid

Number 2 Awg—four-sixty-fourths-inch wall of rubber, rubberized tape and white finished braid

Number 2 Awg—four-sixty-fourths-inch wall of rubber, rubberized tape and four-sixty-fourths-inch wall of lead sheathing

Number 4/0 Awg—five-sixty-fourths-inch wall of rubber, rubberized tape and black finished braid

Number 4/0 Awg—five-sixty-fourths-inch wall of rubber, rubberized tape and white finished braid

500,000 circular mils—six-sixty-fourths-inch wall of rubber, rubberized tape and black finished braid

Table IV. Thermal Surface Resistivities B_b and B_c Under Various Conditions (Braided Cables in Conduit)

Conductor Size (Awg or Mcm)	Number of Cables per Conduit	Nominal Conduit Size (Inches)	Color of Conduit	Loading Current		Thermal Surface Resistivity of Braid Bb (Degrees Centigrade per Watt per Centimeter Square)					Thermal Surface Resistivity of Conduit Bc (Degrees Centigrade per Watt per Centimeter Square)			
						Horizontal		Vertical			Horizontal		Vertical	
				Amps.	Type	Enclosed	Open	Enclosed	Open	Average	Enclosed	Open	Enclosed	Open
12	1	0.50	Black	31	d-c	402	378	351	376	377	948	898	1,061	904
	2	0.50	Black	26	d-c	531	526	477	483	504	897	809	927	858
	3	0.50	Black	20	d-c	581	574	583	535	560	922	824	993	817
	3	0.50	Black	20	a-c	537	551	558	553		931	837	996	852
	3	0.50	White	20	d-c	538	575	595	538		940	804	994	838
2	1	0.75	Black	134	d-c		411			411		840		
	2	1.25	Black	112	d-c		776			776		905		
	3	1.50	Black	100	d-c		1,001			1,001		955		
4/0	1	1.25	Black	260	d-c		622			622		915		
	2	2.00	Black	223	d-c		952			952		1,000		
	3	2.50	Black	200	d-c		1,115			1,115		1,028		
500	1	1.50	Black	450	d-c	716	651	704	701	693	1,081	931	1,256	926
	2	3.00	Black	390	d-c	950	1,022	1,035	1,182	1,047	1,501	1,125	1,604	1,037
	3	3.00	Black	336	d-c	1,030	988	1,063	1,289	1,106	1,307	1,081	1,442	967
	3	3.00	Black	339	a-c	1,025	991	1,083	1,264		1,265	1,083	1,383	962
	3	3.00	White	336	d-c	1,049	1,090	1,137	1,265		1,468	1,050	1,528	899
1,000	2	4.00	Black	638	d-c		1,017			980		1,121		
	2	4.00	Black	548	a-c		940					1,101		

500,000 circular mils—six-sixty-fourths-inch wall of rubber, rubberized tape and white finished braid

500,000 circular mils—six-sixty-fourths-inch wall of rubber, rubberized tape and five-sixty-fourths-inch wall of lead sheathing

1,000,000 circular mils—seven-sixty-fourths-inch wall of rubber, rubberized tape and black finished braid

All of the rubber insulation was of the Code-grade and the saturating and finishing compounds used on the cable were of the flame-retarding, moisture-resisting type per the requirements of The Underwriters' Laboratories. Each type of braided cable was furnished by a different cable manufacturer so as to make the results truly representative.

All tests were conducted in a specially enclosed, draft-free room where suitable sources of a-c and d-c power were available. The 500,000-circular-mil cable and number 12 Awg wire, when measured in air or in conduit, were set up as shown in figure 6. For all other tests the cables were supported horizontally in air or in conduit, three and one-half feet from the floor.

On all horizontal sections, thermocouples were located at approximately 4, 9, and 14 feet from one end of the conduit. On vertical sections, the couples were located at the center and two feet above and below the center. In any one section, thermocouples were placed on the copper, braid, conduit, and in the air, as shown in figure 7.

All thermocouples were made from number 30 Awg enameled, single-cotton-covered, copper and constantan wires. All junctions were soldered and cut to the same length. Cold junctions were immersed in a cup of oil kept in a bath of melting ice.

TEST PROCEDURE

For each test setup, a current, estimated to give 50 degrees centigrade copper temperature, was applied at 8 a.m. This current was maintained for six hours and the first set of readings taken. Readings were repeated hourly until thermal equilibrium had been reached. This procedure was repeated on each setup for three days.

The temperatures at any measuring point were invariably read in the following order, before proceeding to the next measuring point.

1. Conductor temperature (loading current—direct and reversed).
2. Braid temperatures.
3. Conduit to air temperature difference.
4. Air temperature.

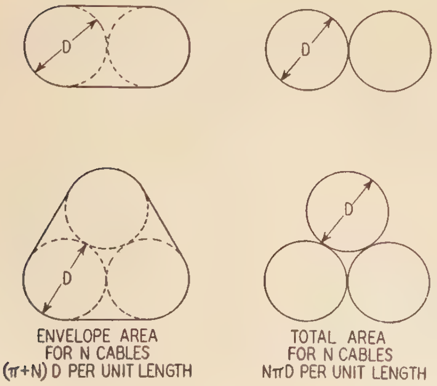

Figure 8. Dissipating surface

The effective resistance for cables in air, was calculated by the use of Ewan's formulae.[24] The effective resistance of cables in conduit was determined by actual measurement. The power input was computed from the current and the effective resistance.

TEST RESULTS

We have already given the test results for the determination of the maximum permissible operating temperature for Code-grade rubber insulation, in figures 2, 3, 4, and 5, respectively.

Tables III, IV, V, and VI, contained the results of all measurements for the determination of thermal surface resistivity for braided cables in air and in conduit, some additional measurements on lead covered cables in conduit, and the a-c resistance of braided and lead covered cables in conduit.

DISCUSSION OF TEST RESULTS

1. The data in table III shows that the value of B_b (thermal surface resistivity of braided cables) in air is not a constant, as previously assumed. For the range of cable sizes investigated, it varies with the over-all diameter of the respective cables. Due to space limitations, only a summary of the data is given, but it can be stated that, although the values of B_b for white finished braids were higher than those for the corresponding sizes with black finished braid, the difference was insufficient to make it necessary to complicate current-carrying capacity calculations by introducing two sets of values. No appreciable difference could be detected in the values of B_b for vertical or horizontal installation.

Table V. Thermal Surface Resistivity B_b (Lead-Covered Cables in Conduit)

Conductor Size (Awg or Mcm)	Over-All Diameter of Cable (Inches)	Number of Cables per Conduit	Nominal Conduit Size (Inches)	Type of Loading Current	Thermal Surface Resistivity B_b (Degrees Centigrade per Watt per Centimeter Square)
2	0.582	2	1.25	a-c	.747
2	0.582	2	1.25	d-c	.711
500	1.240	2	3.00	a-c	.934
500	1.240	2	3.00	d-c	.982

2. The data in table IV indicates the following:

(*a*). The value of B_c (thermal surface resistivity of conduit) is independent of the source of power, the respective values for a given combination of conduit and cable sizes being practically the same whether determined with alternating current or direct current. It should be noted that when computing B_c, care should be taken to use the effective value of R_{cu} for the operating temperature.

(*b*). The value of B_c is independent of the color of the conduit surface, the values being practically the same for black and white conduit. These findings are substantiated by McAdams[25] who, in a table of radiation emissivities for sixteen different colors of oil paint, gives values of 0.92 to 0.96 and also assigns the same value of emissivity for black and white lacquer. It appears that as far as heat dissipation by convection is concerned, the color of the conduit has no significance, but in the case of heat dissipation by radiation, the texture of the surface and the chemical composition of the surface treatment have a far greater effect on heat emissivity than color.

(*c*). The value of B_c increases with increasing conduit diameter.

(*d*). The value of B_c varies with the conduit location, whether it be exposed or concealed, vertical or horizontal. According to McAdams,[25] the air currents passing vertical surfaces are complicated and irregular enough so that the experimental data of several authorities on this subject cannot be successfully correlated. However, he further indicates that for pipes about seven inches in diameter, the convection for a vertical pipe is nearly the same as for a horizontal pipe. This is in substantial agreement with the results as shown in table IV.

To facilitate the use of B_c in the formula for current-carrying capacity, advantage is taken of a correction factor Q, which is discussed elsewhere in the paper.

(*e*). The values of B_b in conduit have been averaged for the respective conduit sizes and cable groupings, so that the resulting values will be truly representative of all of the installation conditions. It should be noted that it is difficult to know the relative position which a group of conductors, when drawn into a conduit, will assume with respect to each other. It should also be pointed out that the respective conduit sizes specified in the Code for certain arrangement of conductors, are based on ease of pulling the conductors into the conduit, and not on a proportional ratio between conductor and conduit diameters. In the light of the foregoing, the data obtained shows excellent agreement with the trend exhibited by the values of B_b in air.

Table VI. A-C/D-C Resistance Ratio (Measured Values for Cables in Iron Conduit)

Conductor Size (Awg or Mcm)	Type of Covering	Number of Cables per Conduit	Nominal Conduit Size (Inches)	Average Ratio A-C/D-C
12	Braid	2	1/2	1.003
12	Braid	3	1/2	1.007
2	Braid	2	1 1/4	1.017
2	Lead	2	1 1/4	1.016
2	Braid	3	1 1/2	1.007
4/0	Braid	2	2	1.034
4/0	Braid	3	2 1/2	1.024
500	Braid	2	3	1.124
500	Lead	2	3	1.224
500	Braid	3	3	1.143
1000	Braid	2	4	1.333

3. Since lead sheathing is used occasionally instead of braid, especially under conditions of moisture, a check was made on the value of B_b in conduit, but using lead covered instead of braided cables. The results are given in table V and show excellent agreement with the values of B_b as shown in table IV.

4. The data in table VI represents the results of a-c resistance determinations for various cable sizes, finishes, and groupings, in the iron conduit sizes prescribed by the code. Each value is the average of two readings, taken with the current direct and reversed, in order to eliminate the effect of stray fields. Among the various factors which have an important bearing on the a-c resistance measurements, are:

(*a*). "Skin effect" in copper conductor, especially larger sizes.

(*b*). "Proximity effect" of one cable upon another, particularly due to the close spacings existing between several cables in conduit.

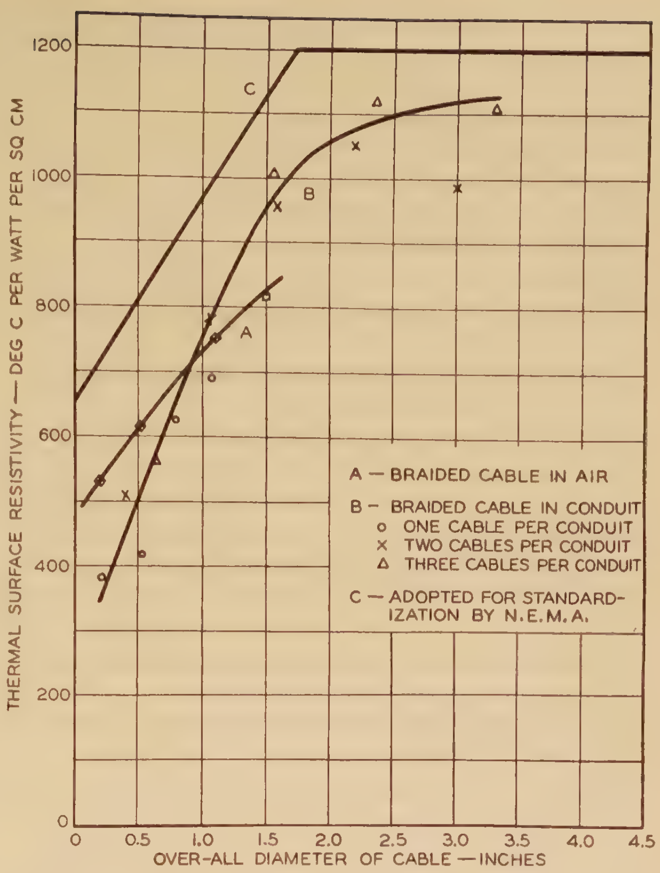

Figure 9. Thermal surface resistivity of cable coverings

(*c*). Hysteresis and eddy currents in the iron conduits causing power losses and increasing the effective resistance of the conductors.

(*d*). In the case of lead-covered cables, there are also eddy-current losses in the lead sheathing, which in turn produce a magnetic field opposite in polarity to that produced by the current in the conductor. Although this reduces the flux in the iron conduit and, consequently, the iron losses, there are heating losses in the lead sheath due to stray currents. If the shielding effect is greater than the sheath loss, the a-c resistance of the lead covered cables will be less than the braided cables, but if the shielding effect is less than the sheath loss, the a-c resistance of the lead-covered cables will be greater than that for the braided cables.

Although table VI contains a considerable number of measurements, it was felt that they were not enough to form the basis for a table of a-c/d-c resistance ratios to be used for computation purposes. Consultation with cable engineers of other cable companies indicated the availability of some additional measurements which enabled the drawing up of a fairly complete set of data. This will be found in table IX.

5. In attempting to calculate the values of B_b in conduit, the question arose as to whether these values should be calculated on the basis of "total" or "envelope area." In order to clarify this point, let us examine the formula for calculating B_b in conduit.

$$B_b = \frac{T_b - T_c}{NI^2R_{cu}} \times \text{dissipating area}$$

wherein

B_b = thermal surface resistivity of braided cable in conduit, degrees centigrade per watt per centimeter square

Table VII. Thermal Surface Resistivity B_b Versus Dissipating Area (Braided Cables in Conduit)

				Dissipating Surface				Thermal Surface Resistivity of Braid B_b Calculated From	
				Envelope Area		Total Area			
Conductor Size (Awg or Mcm)	Over-All Diameter of Cable (Inches)	Number of Cables per Conduit	Nominal Conduit Size (Inches)	Per Foot of Circuit (Cm²)	Diameter of Equivalent Cylinder (Inches)	Per Foot of Circuit (Cm²)	Diameter of Equivalent Cylinder (Inches)	Envelope Area (Degrees Centigrade per Watt per Centimeter Square)	Total Area (Degrees Centigrade per Watt per Centimeter Square)
12	0.216	1	0.50	52.6	0.216	52.6	0.216	378	378
		2	0.50	86.3	0.354	105	0.432	431	526
		3	0.50	103	0.421	158	0.648	373	574
2	0.518	1	0.75	126	0.52	126	0.518	411	411
		2	1.25	207	0.85	252	1.04	636	776
		3	1.50	246	1.01	378	1.55	652	1,001
4/0	0.784	1	1.25	191	0.79	191	0.785	622	622
		2	2.00	313	1.29	382	1.57	781	952
		3	2.50	373	1.54	573	2.35	726	1,115
500	1.100	1	1.50	267	1.10	267	1.10	651	651
		2	3.00	438	1.81	534	2.20	840	1,022
		3	3.00	522	2.15	801	3.30	644	988
1,000	1.50	2	4.00	596	2.45	730	3.00	830	1,017

T_b = temperature of the braid, degrees centigrade
T_c = temperature of conduit, degrees centigrade
N = number of cables in conduit
I = current in amperes
R_{cu} = effective conductor resistance at maximum operating temperature, ohms per ft.

The dissipating surface may be considered as either of the areas shown in figure 8 and since there was no precedent available in the literature as to which should be used calculations were made with both the "envelope" as well as the "total area." The resulting values of B_b have been incorporated in table VII and, as can be seen, the values are more consistent when computed on the basis of "total area." This can be more readily seen from a study of curve B in figure 9. It will be noted that almost all of the points lie on this curve, even though the points represent values for one, two, and three cables per conduit. Therefore, all of our values for B_b in conduit are based on a dissipating surface defined as the "total area."

Table VIII. Conduit Correction Factor Q

	Values of Q		
	No. of Single or Multi-Conductor Cables per Conduit		
Nominal Conduit Size Inches	One	Two	Three
0.50	3.9	9.5	15.4
0.75	3.6	8.6	13.9
1.00	3.2	7.6	12.4
1.25	2.8	6.7	11.0
1.50	2.6	6.2	10.2
2.00	2.3	5.5	8.9
2.50	2.1	4.8	7.6
3.00	1.9	4.2	6.6
3.50	1.8	3.8	6.0
4.00	1.7	3.5	5.5
4.50	1.6	3.3	5.2

NOTE: *a.* The above values refer to number of cables in a conduit, not to number of conductors in a conduit.
Example: The correction factor for one three-conductor cable in a two-inch conduit is 2.3, while for three single-conductor cables in same size conduit, it is 8.9.
b. Tables do not extend beyond 4.5 inch nominal conduit size because of unknown losses when very large conductor sizes are used.

6. After curves A and B in figure 9 had been plotted, it was felt that some factor of safety should be introduced. After a thorough review of the subject by the technical representatives of the respective Wire and Cable Sections of NEMA, curve C in figure 9 was chosen for standardization as representative of the values of B_b for braided or lead covered cables, in air or in conduit. This curve is a straight line from a value of 650 at 0 diameter to a value of 1,200 degrees centigrade per watt per centimeter square, for a diameter of 1.75 inches and continuing in a horizontal straight line thereafter at a constant value of 1,200 degrees centigrade per watt per centimeter square.

DERIVATION OF CONDUIT CORRECTION FACTOR Q

To understand the significance of the conduit correction factor Q and its function in the calculation of current-carrying capacity, let us consider the case of a single conductor cable, suspended in free air. In an installation of this type the cable creates a "uniform" heat field and its current-carrying capacity may be expressed by

$$I = \sqrt{\frac{T_0 - T_a}{R_{th} R_{cu}}} \text{ amperes} \tag{1}$$

$$R_{th} = 0.00522\, \rho \log_\epsilon \frac{D}{d} + 0.00411 \frac{B}{D} \text{ thermal ohms per foot} \tag{2}$$

wherein

R_{th} = thermal resistance of path from conductor to ambient air, thermal ohms per foot
ρ = 500 degrees centigrade per watt per centimeter cube
D = over-all diameter of cable, inches
d = diameter over copper conductor, inches
B = thermal surface resistivity of the cable in still air, degrees centigrade per watt per centimeter square
T_0 = maximum permissible operating temperature of conductor, degrees centigrade
T_a = ambient temperature, degrees centigrade
R_{cu} = effective conductor resistance at operating temperature, ohms per foot

If we now introduce a conduit into this "uniform" heat field, the latter is distorted and the thermal resistance is increased. The amount of this increase, we define as Q, or the correction factor made necessary by the introduction of the cable in a conduit. As a result of the new thermal resistance, equation 2 now becomes:

$$R_{th}' = 0.00522\,\rho \log_e \frac{D}{d} + 0.00411\,\frac{B}{D} + Q \text{ thermal ohms per foot} \quad (3)$$

or

$$R_{th}' = R_{th} + Q \qquad \text{thermal ohms per foot}$$

The derivation of the values of Q for any given set of installation conditions, may be experimentally determined by measurements made on an actual setup of cables in conduit, as follows:

From equation 1

$$I^2 R_{cu} R_{th} = T_0 - T_a$$

substituting the new value of R_{th} from equation 3, we have

$$I^2 R_{cu}\left(0.00522\,\rho \log_e \frac{D}{d} + 0.00411\,\frac{B}{D} + Q\right) = T_0 - T_a$$

and

$$Q = \frac{T_0 - T_a}{I^2 R_{cu}} - \left(0.00522\,\rho \log_e \frac{D}{d} + 0.00411\,\frac{B}{D}\right)$$

The values of T_0, T_a, I, R_{cu}, D, and d are all obtained from actual measurements and B is taken from the standard curve. Experimental determinations conducted in this manner, indicate that for a given size of conduit containing a given number of cables, the conduit correction factor Q is independent of cable diameter. Values of Q based on the data obtained during the NEMA investigation, will be found in table VIII.

The conduit correction factor Q makes it unnecessary to use the value of B_c (thermal surface resistivity of the conduit) in the formula for R_{th}, since Q contains the elements from which B_c would ordinarily be calculated.

Table IX. A-C/D-C Resistance Ratio

Conductor Size (Awg or Mcm)	A-C/D-C Resistance Ratio: Single Conductor Cable in Air or Separate Nonmetallic Conduit	A-C/D-C Resistance Ratio: Multiconductor Cable or Two or Three Single-Conductor Cables in Same Conduit
Up to 3	1.00	1.00
2 and 1	1.00	1.01
1/0	1.00	1.02
2/0	1.00	1.03
3/0	1.00	1.04
4/0	1.00	1.05
250	1.005	1.06
300	1.006	1.07
350	1.009	1.08
400	1.011	1.10
500	1.018	1.13
600	1.025	1.16
700	1.034	1.19
750	1.039	1.21
800	1.044	
1,000	1.067	
1,250	1.102	
1,500	1.142	
1,750	1.185	
2,000	1.233	

Formulae for Current-Carrying Capacity Calculation

The formulae for current-carrying capacity and thermal resistance of one, two, and three, single- or multiconductor cables installed in conduit, are:

$$I = \sqrt{\frac{T_0 - T_a}{n\,R_{cu} R_{th}}} \text{ amperes}$$

and

$$R_{th} = \frac{0.00522\rho\,G_1}{n} + \frac{0.00411B}{D} + Q \text{ thermal ohms per foot of cable}$$

wherein

T_0 = maximum safe operating temperature, degrees centigrade. For Code-grade rubber insulation, T_0 = 50 degrees centigrade.

T_a = ambient temperature, degrees centigrade. For building installations T_a = 30 degrees centigrade

n = number of conductors in a cable.

R_{cu} = effective resistance of copper conductor, ohms per foot. For d-c resistance use values given in National Bureau of Standards Circular 31, for 100 per cent IACS conductivity and corrected to proper operating temperature. For a-c/d-c resistance ratio, use values in table IX.

ρ = thermal resistivity, degrees centigrade per watt per centimeter cube. For rubber insulation = 500. For tape or braid over rubber insulation use same value.

G_1 = geometric factor to be taken from Simmons[18] or Underground Systems Reference Book,[1] page 297. In computing the geometric factor consider the tape and/or braid on single conductor cables, and tape of individual conductors of multiconductor cables, as part of the insulation. Tape and braid over assembled conductors are to be considered as belt insulation.

B = thermal surface resistivity, degrees centigrade per watt per centimeter square. For braid, lead and other coverings, use values from curve C in figure 9. The value of B can also be determined as follows:

For diameters below 1.75 inches: $B = 314D + 650$
For diameters 1.75 inches and larger: $B = 1{,}200$

D = over-all diameter of cable, inches.

Q = conduit correction factor. Values to be taken from table VIII. The respective conduit sizes to be in accordance with the National Electrical Code.

AMBIENT TEMPERATURE

Under the formula for current-carrying capacity, we listed T_a = 30 degrees centigrade. Our investigation indicates that 30 degrees centigrade (86 degrees Fahrenheit) is a fair average ambient temperature for indoor installations in general and, accordingly, this value has been chosen by NEMA as standard for all future calculations of interior wiring problems. There may, of course, be conditions of installation where it is definitely known that the temperature of the surroundings is other than 30 degrees centigrade, in which case the correction factors given in table X should be applied to the standard values computed on the basis of a 30 degrees centigrade ambient.

CABLE RATINGS BASED ON NEMA INVESTIGATION

In table I given in the earlier part of the paper, an attempt was made to bring together under one tabulation, all of the principal tables of current carrying capacity for rubber insulated conductors from 1889 to 1937. Included in that tabulation, were excerpts from the present IEE wiring rules[21] issued in 1934, and attention is directed to the fact that the latter have recognized the distinction between a-c and d-c current ratings, especially in the case of the larger conductors. It is also of interest to note that in contrast to our own code ratings, the IEE wiring rules provide ratings for various conductor groupings or conductor assemblies, and that these ratings are based on a definite ambient temperature and a definite maximum permissible temperature rise, a practice which conforms to the best universal engineering thought on the subject. Even in 1903, the IEE[13] made a distinction between high and normal ambients.

In table XI, we have tabulated some cable ratings, based on the factors established by the NEMA investigation, for a single cable in air, and three cables in iron conduit. The calculations were made both for a-c, as well as d-c, loadings. For comparative purposes, we have also included in this tabulation, the corresponding ratings taken from the 1937 edition of The National Electrical Code.[23] It may be of interest to compare the respective ratings for number 4/0 Awg cable. For three 4/0 Awg single cables in iron conduit, carrying alternating current, the data indicates approximately 160 amperes as compared to 225 amperes permitted by the Code. Under these conditions of installation, three 4/0 Awg cables, carrying 225 amperes per cable, would actually achieve a maximum temperature at the surface of the conductor of approximately 66 degrees centigrade.

Conclusions

The factors established in this investigation are equally applicable to varnished cambric, and impregnated paper-insulated cables, as well as to rubber-insulated cables. The formulae are applicable, not only to Code-grade rubber insulations, but to all other grades as well, the important point being to have definite knowledge concerning the maximum permissible operating temperature of the particular insulation in question.

It is the author's hope that the results of this investigation will not only be reflected in a revision of future Code ratings for rubber-insulated cables, but that the factors established by this investigation will be used by others for the revision of existing current-carrying capacity tables for other types of insulated cables as well.

Table X. Correction Factors for Change in Ambient Temperature Based on Maximum Operating Temperature of 50 Degrees Centigrade

Ambient Temperature (Degrees Centigrade)	Correction Factor
10	1.42
20	1.23
30	1.00
40	0.71

Note: For ambients higher than 40 degrees centigrade, insulations other than Code-grade rubber, having a higher permissible operating temperature, should be used.

Acknowledgments

To Anaconda Wire and Cable Company and its engineering staff for the use of laboratory and other facilities: to the Rubber Covered Building Wire Section of NEMA for sponsoring this investigation and for permission to publish these results: to Mr. E. D. Youmans, chairman of the NEMA building wire technical committee: to the members of the technical committee of the Rubber Covered Building Wire Section and the Rubber and Varnished Cambric Power Cable Sections of NEMA, for their very kind criticisms and many helpful suggestions: to all of these and many others who may have contributed to the completion of this investigation, the author wishes to convey his sincere gratitude.

Table XI. Cable Ratings Based on NEMA Investigation

Conductor Size (Awg or Mcm)	Current-Carrying Capacity in Amperes				
	Based on Constants From NEMA Investigation				
	Alternating Current		Direct Current		
	One Cable in Air	Three Cables in Conduit	One Cable in Air	Three Cables in Conduit	1937 National Electrical Code
14	20	15	20	15	15
12	26	19	26	19	20
10	34	26	34	26	25
8	48	35	48	35	35
6	66	47	66	47	50
4	88	61	88	61	70
2	118	78	118	79	90
1/0	160	105	160	106	125
2/0	185	119	185	121	150
3/0	215	141	215	144	175
4/0	249	160	249	164	225
500	430	267	433	284	400
800	571	345	584	384	550
1,000	653		675		650

Note: The above calculations are based upon conduit sizes recommended by the National Electrical Code.

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Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 2 pages appear all remaining discussions submitted for publication, and approved by the technical committees, on papers presented at the AIEE Pacific Coast convention, Spokane, Wash., August 31–September 3, 1937; and at the AIEE Middle Eastern District meeting, Akron, Ohio, October 13–15, 1937. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Regulation of Grid-Controlled Rectifier

Discussion and authors' closure of a paper by L. A. Kilgore and J. H. Cox published in the September 1937 issue, pages 1134–40, and presented for oral discussion at the electronics session of the AIEE Middle Eastern District meeting, Akron, Ohio, October 14, 1937.

E. H. Reid (General Electric Company, Schenectady, N. Y.): Messrs. Kilgore and Cox have given a very interesting paper on regulation of grid controlled rectifiers. In regard to the effect of grid characteristics on regulation, I would like to say that it is our experience that most practical commercial designs have what we call a positive characteristic throughout the guaranteed load range. That is, the potential applied to the grid must be positive with respect to cathode before the anode will fire. This being the case, the effect of the grid characteristic on regulation we believe would be small.

I would like to add that by a simple manipulation of a few watts of grid control power the regulation of a grid controlled rectifier may be corrected or changed almost at will.

I would like to suggest that some indication of magnitudes on figure 6 would be of interest. I assume that cathode potential is referred to as 0 potential in this diagram.

W. M. Goodhue (Harvard University, Cambridge, Mass): The authors should be commended for quantitative study of abnormal regulation in grid-controlled rectifiers, particularly where system reactance, or smoothing deficiency at light load are involved.

In figure 2 are shown rectifier characteristics for the increase in regulation due to system reactance, and most of these characteristics show a high degree of curvature. Usually, rectifier regulation characteristics are essentially straight lines, such as those in figure 1. The authors do not give any physical explanation of this curvature. Such an explanation would be very helpful to the writer particularly in his understanding of other factors along these lines.

Is it possible that the assumption on page 1135 of "fundamental frequency voltage E, at the primary terminals may be taken equal to the root-mean-square value" is the cause of the curvature? It would be expected that the effect of system reactance is to increase the "*source*" voltage *linearly* at the same time that the regulation is linearly increased. This is because the effect of reactance is to introduce large harmonic voltage drops, in addition to ordinary phase lag and sine wave drops. Without taking the time to analyze thoroughly the problem, I would expect such a method, when employed with only two anodes involved in commutation, to be useful only in the straight line portions of the curves.

The discussion of light load voltage rise on pages 1136–7, taking grid delay and interphase into account, is very clear and provides a useful graphical method.

If grid delay is used in circuits having interphase transformers there arises the question as to the proper distribution of average current between the two halves of the interphase winding at loads greater than critical, say full load. The grid control is responsible in large measure for the average voltage output of each of the anode groups (double-three-phase circuit). Unlike conditions without grids, any unbalance of these voltages caused by grid control will greatly affect the average current distribution in the interphase, since inductance is powerless to limit the flow of average current. Since the paper implies the use of interphase transformers with grid control, it would be very important to know the average current distribution in the two halves of the interphase, at various loads, particularly from half load to full load and overload, for various delay angles (α). Have the authors any information on the interphase current distribution, at least at full load, and at one or more typical grid delay angles? The distribution is important commercially in that input current harmonics, output voltage harmonics, and limit of load by heating of transformer and rectifier may be affected. For example, a three-phase rectifier has a *second harmonic* of input current which will be introduced by the unbalance of a double-three-phase circuit.

L. A. Kilgore: Mr. Goodhue asks the cause of the curvature of the curves for the correction to be applied for system reactance. It is true that the drop in voltage due to commutating reactance is proportional to the total reactance. However, the increase in the sine-wave voltage for a given primary voltage is not proportional, since the reactive drop adds vectorially. This causes the source voltage to increase more than proportionally, which is offset by a proportional reduction; hence, the net correction to regulation increases less than proportionally.

Mr. Reid has asked concerning the scale of figure 6. This is about 20 volts per division and the voltages are measured relative to the cathode. It is true that if the grid characteristics are positive throughout the range, they will make very little difference on the pick-up provided several hundred volt impulses are used on the grids. However, the authors do not consider that this is essential if the characteristics do not go too much negative throughout the operating range.

Empirical Method of Calculating Corona Loss From High-Voltage Transmission Lines

Discussion and authors' closure of a paper by Joseph H. Carroll and Mabel Macferran Rockwell published in the May 1937 issue, pages 558–65, and presented for oral discussion at the power transmission and distribution session of the AIEE Pacific Coast convention, Spokane, Wash., September 1, 1937.

E. C. Starr (Oregon State College, Corvallis): The paper by Mrs. Rockwell and Doctor Carroll is interesting and valuable in that it summarizes a great deal of corona loss information, which has been obtained over a long period of time, and makes it available in a general way for future application.

The problem is an old one and has been attacked by a great many investigators. Formulas which give reasonably accurate data for losses of the order of five to ten kw per mile of three-phase line were developed by F. W. Peek, Jr., and his associates over 20 years ago. The important thing today, however, is to be able to design a line which will be known to have only a very small amount of corona loss under normal operating conditions. The data contained in this paper for the one-kw-per-mile condition are very valuable and are not obtainable accurately by calculation from any existing formula. It will become increasingly desirable that we reduce corona losses from transmission lines to values even less than one kw per mile, and there is need for an accumulation of data showing the practical starting point of corona on the various sizes and types of conductors used in modern transmission line practice. I realize that the starting point of corona is a very indefinite thing and that we should specify some definite loss as indicating the starting point. The figure of 100 watts per mile of three-phase line might be sufficiently close to the actual starting point to be satisfactory for most applications.

From the standpoint of the power saved, the reduction of losses below a few kw per mile is not especially justifiable, but the problem of interference with radio reception, particularly on the short-wave bands, is becoming increasingly acute. Information is not available on the magnitude and coverage of interference created by corona loss of different power values from transmission circuits, but observation has shown that a degree of loss which is economically satisfactory produces a great deal of interference which blankets a fairly wide area in the short-wave radio communication bands.

An interesting case is that of the Pitt River lines of the Pacific Gas and Electric Company in Northern California. The Seattle-San Diego Airway crosses this line several miles south of Mt. Shasta and parallels it at some distance for a number of miles. At altitudes as great as 14,000 feet a considerable amount of interference is created by this line in the short-wave radio receivers of the transport planes. This interference is not ordinarily so great as to render normal communication ineffective, but it is nevertheless disturbing. This line is, of course, a rather old one and was designed to operate in a small amount of corona. It would be interesting to know just how much loss per mile is occurring from that particular transmission line in the vicinity of the airway crossing.

Present-day conductor design has advanced to the point where it is economically feasible to reduce corona losses to zero, or nearly so, for all normal operating conditions and it is felt that all future lines should be designed with the objective in view of reducing corona loss to an absolute minimum. The industry would be greatly benefited by the publication of a carefully compiled set of data showing the initial corona points for practical transmission line conductors under different conditions of altitude and atmospheric temperature.

M. M. Rockwell: Professor Starr's discussion hits the nail squarely on the head in stating that economic considerations are not the only ones to be taken into account in determining how much corona loss is permissible on a line. The matter of radio interference is undoubtedly of importance too, especially where the line traverses populous territory.

I should like to speak a word of caution, however, against taking even the radio angle too seriously. To begin with, the Pitt River line which Professor Starr cites as disturbing airways communication, is made up of rope-lay cable and is known to be operating with much heavier corona than is permitted on any lines of more recent design. In the second place, much or all of the disturbance commonly attributed to corona on so-called noisy lines is actually caused by corona on sharp-edged hardware and fittings, not on the conductor itself. This has been verified by examinations made in the dead of night on various Southern California high-voltage lines operating at high altitudes. These lines were very noisy and caused appreciable interference on car radios, yet examination showed no corona whatever on the conductors themselves, but copious brushes from the suspension clamps, vibration dampers, and occasionally the splices. Hence it would be well to eliminate these sources of trouble before turning too much suspicion on the conductor itself. In fact, I have heard my colleague, Doctor Carroll, state that he once made radio interference studies in the high-voltage laboratory at Stanford, in which the conductors were allowed to go into copious corona, yet little or no interference could be detected in the radio set. At the same time, if brushes were allowed to form on the hardware or insulators, interference resulted. Apparently the inductive-capacitive circuit conditions necessary for setting up radio waves were not present in simple corona from line conductors, and only occurred where small gaps between fittings, etc., were broken down. Of course, I do not know whether this analysis extended to the ultra-short waves now used in radio work. In any event I believe that a good deal of careful experimentation on radio interference due to corona from the conductor itself should be carried on before jumping to the conclusion that conductors should be operated below the corona starting point to avoid interference. If this rule were adopted it would cause the cost of lines to jump appreciably, as the economic balance-point appears to be such as to permit a loss amounting to several kilowatts a mile. The pronounced flattening of the corona curves at the lower end indicates that the size conductor for a given voltage would have to be very markedly increased to avoid the chance of one or two brushes appearing per span, especially in foggy weather. Perhaps it will be found that if brushes from hardware, etc., are eliminated, these one or two brushes on the conductor itself will do little or no harm.

In designing the 220-kv lines for transmitting power from Boulder Dam to the pumping plants along the aqueduct of the Metropolitan Water District of Southern California, with which the writer was associated, it was found economic to permit quite a bit of corona on the lines. Since these lines passed through desert territory the radio interference problem did not seem of importance. Nevertheless, the conductor diameter was selected large enough to limit the corona to quite low values, just to be on the safe side. The matter of airways communication was not thought of at the time, but perhaps from this standpoint, the conservative design in the matter of corona will prove a good thing.

Present-Day and Probable Future Electrical Applications in Aircraft

Discussion and author's closure of a paper by W. V. Boughton published in the August 1937 issue, pages 959–63, and presented for oral discussion at the selected subjects session of the AIEE Pacific Coast Convention, Spokane, Wash., August 31, 1937.

E. C. Starr (Oregon State College, Corvallis): It is interesting to note how completely the modern aircraft are becoming electrified. In the past it has been possible to employ storage-battery and low-voltage systems quite satisfactorily in most transport work but, as indicated by Mr. Boughton, we will soon be compelled to go to higher voltages and much greater power capacities. He indicates that alternating current of a frequency probably between 360 and 800 cycles will be employed. There is some question as to whether single- or three-phase supply will be chosen. It is true that polyphase motors have an advantage over single phase but for frequencies as great as 800 cycles the single-phase capacitor motor should be almost ideal. It would be light in weight since it would require only a small amount of iron and copper, and modern high-capacitance capacitors are available in very small sizes. The simplicity of the single-phase system, together with the efficiency of capacitor motors, should be given careful consideration in the final choice.

The higher power frequencies employed in connection with the radio equipment will make necessary more careful filtering and shielding than is employed at present to prevent undesirable speech interference. This problem, however, should not be at all difficult.

It is interesting to note here that in addition to the regular electrical equipment which one might expect to find on all large transport planes, we may soon have rather complex rain- and snow-static discharging devices. Intense radio interference produced by certain storm conditions makes the development of such equipment desirable. Storm-static research during the past few months has clarified the problem and indicated the necessary developments.

W. V. Boughton: Motor applications in aircraft are rapidly increasing, and the use of motors as large as ten horsepower is quite probable. It is rather doubtful whether the use of single-phase capacitor motors would be desirable for these sizes. Three-phase supply presents no serious distribution problems and does present advantages when synchronization of two or more generating units is considered.

The saving in weight of motors at 800 cycles over 400 cycles is extremely doubtful when the capacitor weight and reduction gearing is considered. In many cases mechanical limitations in manufacturing may prevent taking full advantage of the theoretical weight saving at 800 cycles.

The problem of radio interference from the higher power frequencies has been studied by the radio manufacturers and can be readily solved.

Extension of 2-Reaction Theory to Multiphase Synchronous Machines

Discussion and author's closure of a paper by Y. H. Ku published in the September 1937 issue, pages 1197–1201.

R. H. Park (The Calco Chemical Company, Inc., Bound Brook, N. J.): It may be desirable, in connection with this paper, to point out that the assumption that all space harmonics are zero and further that the mutual slot leakage reactance is space fundamentally distributed departs from the assumptions of reference 11 of the paper wherein it was merely assumed that "as far as concerns effects depending on the position of the rotor, each armature winding is sinusoidally distributed.

On the basis of the latter assumption β in equation 3 of appendix I would be regarded as merely the space fundamental component of air gap flux and the total linkages in phase a would be computed as $\psi_a(\beta) + \psi_a(l)$ where by symmetry

$$\psi_a(l) = -x_{l\sigma}i_a + x_{map}(i_b + i_n) + x_{mac}(i_c + i_{n-1}) + x_{mad}(i_d + i_{n-2}) + \ldots\ldots$$

and the x_m's are suitable mutual coefficients which may be either positive or negative, but which take into account the detail nature of the slot mutual and harmonic air gap fluxes, which are merely assumed to be unaffected by rotor position.

But for a three-phase machine we have in general, with balanced terminal connections, under transient as well as steady conditions, $e_a = \mathbf{e}\cdot\mathbf{a}$, $\psi_a = \psi\cdot\mathbf{a}$, $i_a = \mathbf{i}\cdot\mathbf{a}$ where $\mathbf{e}$, ψ, and $\mathbf{i}$ are instantaneous space vectors and $\mathbf{a}$ is a unit space vector representing the position of any phase a.

Evidently we may tentatively assume that the same type of relationship holds generally for a multiphase machine. On this assumption and if the number of phases n is equal to or greater than three, it would follow from equation 6 of reference 11, after making the necessary changes in notation that if ϕ is the angle between $\mathbf{i}$ and $\mathbf{a}$ and $\theta = \phi + \theta_0$, $\theta_0 = 360/n$ that $i_a = \cos\phi$, $i_b = i(\cos\phi - \theta_0)$, etc.,

$$\psi_a = I_d\cos\theta - I_q\sin\theta - \left(x_{l\sigma} + x_m + \frac{p_d + p_q}{2}\right) i\cos\phi - \frac{p_d - p_q}{2}\cos(\phi + 2\phi_0)$$

where

$$x_m = -2(x_{mab}\cos\theta_0 + x_{mac}\cos 2\theta_0 + \ldots\ldots)$$

a result which may be seen to be independent of n.

But as this is the same form as the corresponding equation for a three-phase machine it will be apparent that the validity of the tentative assumption stated, namely, that the space vectors $\mathbf{e}$, ψ, and $\mathbf{i}$ which correspond to the behavior of a three-phase machine do in fact represent the vector form of the solution for any machine of three or more phases under any balanced terminal conditions whether transient or not, has been demonstrated.

But under balanced load conditions a two-phase machine would behave in the same way as a four-phase machine, in view of symmetry conditions.

Hence we may conclude that any solution of the equations of a three-phase machine under balanced load conditions may properly be thought of as automatically constituting a solution for a machine of any number of phases in excess of one.

Y. H. Ku: The author appreciates very much the discussion of Mr. R. H. Park regarding the assumptions in appendix I. Though the armature-reaction linkages are free from space harmonics as given by equation 4, the simplification that the mutual slot leakage reactance is space fundamentally distributed is not necessary, as rightly pointed out by Mr. Park. So, in general, equation 5 may be written as follows:

$$\psi_A = \psi_{A(\beta)} + \psi_{A(l)}$$

where $\psi_A(\beta)$ is given by equation 4 in appendix I and

$$\psi_{A(l)} = -x_{l\sigma}i_A - [x_{mAB}i_B + x_{mAC}i_C + \ldots\ldots + x_{mAN}i_N]$$

From symmetry, $x_{mAB} = x_{mAN}$, and similarly for others. These x_m's are mutual coefficients which take into account the detail nature of the slot mutual and harmonic air gap fluxes.

Under balanced conditions, there are

$i_A\cos t$, $i_B\cos(t - \theta_0)$, etc.

where $\theta_0 = 2\pi/n$ and n is the number of phases.

Substituting these current expressions, we get

$$\psi_{A(l)} = -[x_{e\sigma} + x_{mAB}\cos\theta_0 + x_{mAC}\cos 2\theta_0 + \ldots\ldots + x_{mAN}\cos\theta_0]\cos t$$

Notice that the above expression holds for any number of phases, even or odd. For n odd, it can be easily seen that the sin t terms cancel each other on account of symmetry. For n even, however, we have a mutual term involving $\cos[t - (n/2)\theta_0]$ which can be expanded into $[\cos t\cos(n/2)\theta_0 + \sin t\sin(n/2)\theta_0]$. Now since $\theta_0 = 2\pi/n$, $\sin(n/2)$, θ_0 is zero, and hence there will be no sin t terms.

Equation 6 of appendix I can then be rewritten as

$$\psi_A = -\left[x_{l\sigma} + x_m + \frac{p_d + p_q}{2}\right] - \cos t\,\frac{p_d - p_q}{2}\cos(t + 2t_0)$$

where

$$x_m = x_{mAB}\cos\theta_0 + x_{mAC}\cos 2\theta_0 + \ldots\ldots\ldots + x_{mAN}\cos\theta_0$$

With this new expression of x_m, equations 7 and 8 are also extended to the more general form. However, x_0 in equation 9 should be changed to the following:

$$x_\theta = x_{l\sigma} + x_{mAB} + x_{mAC} + \ldots\ldots\ldots + x_{mAN}$$

Transactions

Papers and Discussions Comprising Pages 171–226 of the 1938 Volume

Sharp Cutoff in Vacuum Tubes, With Applications to the Slide-Back Voltmeter

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Synopsis: That the current-voltage characteristics of vacuum tubes obey an exponential law near cutoff is pointed out. The larger the coefficient *k* appearing in the exponent, the steeper will be the current-voltage curve, and the better suited the tube will be for use in a slide-back voltmeter. The problem of obtaining high values of *k* is considered, and a simple theory of rectification by an exponential conductor is given. The error inherent in slide-back voltmeters of the ordinary type is discussed, and a correction factor applicable to sine waves is derived. The circuit of a slide-back vacuum-tube voltmeter which includes means for measuring the *k* of the tube is shown.

WHEN a high-vacuum tube is used as a small-voltage rectifier, or as a threshold indicator, it is usually desirable that the current-voltage curve have as abrupt a cutoff as possible. In many cases a sharp angle at the foot of the characteristic would be valuable, but, since this cannot be realized in a high-vacuum device, we must be content with obtaining a rapid rise in current as the control voltage is increased in the positive direction.

Despite the fact that many very satisfactory forms of direct-reading vacuum-tube voltmeters have been developed during the last few years, the slide-back[1,2] type is still an extremely useful instrument. In this type, a triode, or multielectrode tube, is biased almost to cutoff, and the reading of a d-c voltmeter which indicates the bias is noted. The signal to be measured is then applied to the grid in series with the bias voltage, and the bias is increased until the cutoff point is again reached. The difference in the two readings of the d-c voltmeter equals the peak value of the alternating voltage under measurement. The simplicity of this instrument, together with the fact that an accurate d-c voltmeter may be used to measure a-c peak voltages, makes it the most suitable device for many applications. Moreover, it is easily built and manipulated by men who have had no experience with vacuum tube circuits.

However, the slide-back voltmeter will give accurate results only if the voltage under measurement is reasonably large. When taking a reading with it, we must allow the peak of the impressed alternating voltage to swing past cutoff by an amount sufficient to produce a detectable current in the plate circuit of the tube. Just how much past cutoff this is is not ordinarily known, and consequently an uncertainty is introduced into the reading. If the potential under measurement is only a few volts, a considerable error may result.

In this paper, a study is made of the conditions which lead to the most rapid rise of the plate current versus grid voltage characteristic of a vacuum tube, and the results are applied to the operation of a slide-back voltmeter. The error involved in the measurement of small voltages is discussed, and a correction factor is derived which makes it possible to obtain accurate measurements of sinusoidal waves having peak values of as little as half a volt.

Form of Current-Voltage Curves

At very low currents, the theoretical equation of a diode is given by[3]

$$I = I_s \epsilon^{\frac{-eV}{KT}} \tag{1}$$

in which V is the voltage between the electrodes, I_s is the saturation current, T is the absolute temperature, e is the charge of an electron $= -1.59 \times 10^{-19}$ coulombs, and K is Boltzmann's constant $= 1.37 \times 10^{-23}$ joules per degree. Actually, the grid current-grid voltage characteristic of commercial high-vacuum tubes is found to be exponential in form over a limited range.

Let the coefficient of V be represented by k. Then, putting in the numerical values quoted, there results

$$k = \frac{-e}{KT} = \frac{11{,}600}{T} \tag{2}$$

Then

$$I = I_s \epsilon^{kV} \tag{3}$$

We may evaluate k experimentally at any given temperature. Its value for the grid voltage-grid current curve of average receiving tubes lies between 5 and 11, and the exponential law holds over a range of about 0.6 volts.

The quantity I_s is of no great interest to us here, since the factor which multiplies the exponential term in the current equation can be varied at will by adjusting the bias

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[1] For all numbered references, see list at end of paper.

voltage. Thus, if we apply a bias $-V_0$ and a variable voltage v, (3) gives

$$I = I_s \epsilon^{kV_0} \epsilon^{kv} = G\epsilon^{kv} \tag{4}$$

G being a new constant. Evidently, it is k, and not I_s, which, from a circuit-theory standpoint, is an important parameter of a given tube.

In the case of a multielectrode tube, there is, of course, no necessary relation between the plate current-grid voltage characteristic and the curve defined by (1), since the degree of control which the grid exercises upon the electron stream is dependent upon a number of different factors. However, it is not unreasonable to suppose that, with an efficient grid structure allowing very little leakage of lines of force around it, the equation for low currents might be similar to (1). The most efficient grid structure encountered in ordinary tubes is that of the screen in a tetrode or pentode. We may expect that when the screen is used as the control element, a more rapid variation of plate current with grid voltage will be obtained near cutoff than when the ordinary grid is used. Whether or not the current-voltage curve is exponential is best determined by experiment.

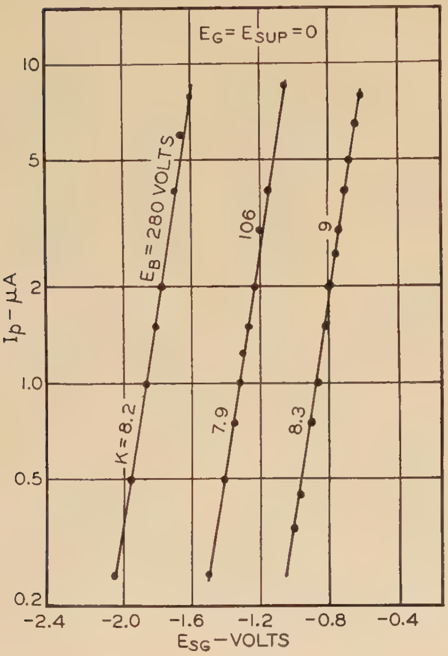


Figure 1. Curves of plate current versus screen-grid voltage for a type 77 tube

It is to be noted that plate voltage has only a small effect on the slope of these curves

Figure 1 shows semilogarithmic plots which were taken of the plate current-screen voltage characteristics of a type 77 vacuum tube, the suppressor and control grid being connected to the cathode. The three curves are for widely different values of plate voltage, and it is to be seen that an exponential law is obeyed in all three cases. Furthermore, the slope of all the curves is practically the same.

Figure 2 shows $I_p - E_{sg}$ characteristics of two other type 77 tubes and one 6*D*6. The former are exponential up to about ten microamperes, and the latter to about five microamperes.

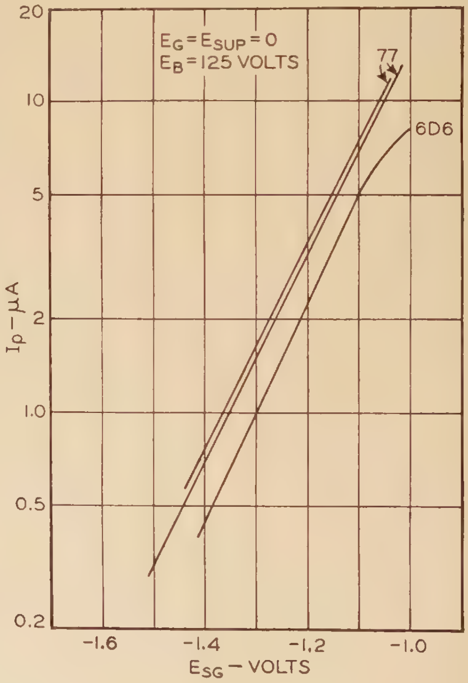
Strictly speaking, an exponential characteristic has no cutoff point, since the curve approaches the voltage axis asymptotically. In practice, however, the plate current is regarded as being cut off when it is reduced to so small a value that it can no longer be read on the plate-circuit microammeter. As the control element is made less negative, the meter will finally show a reading, which will then increase, as the control voltage is further changed, with a rapidity that is determined by the constant k of (3). The larger k is, the more abrupt is the rise of current, and hence the more satisfactory the tube will be for use in a slide-back voltmeter or similar device.

The values of k determined graphically from the slopes of the curves of figure 1 are marked on them, and it will be seen that k is not greatly dependent upon the plate voltage. With such steep slopes, the graphical determination may easily be in error by several units in the second digit, and consequently we may say that k is roughly constant with respect to plate voltage.

Effect of Operating Conditions on k

The curves of figure 1 have shown the small effect of changes in plate voltage on k. Figure 3 shows a group of curves, taken on another type 77 tube, in which the suppressor voltage is the parameter. Here again an exponential law is obeyed over the range which was measured. The graphically determined values of k are again shown on these curves, and it is evident that suppressor voltage has no marked effect upon this quantity, although positive voltages tend to reduce it somewhat.

Figure 2. Curves of plate current versus screen-grid voltage for two different model 77 tubes and a 6D6



Having established the fact that the current-voltage characteristics with which we are dealing are substantially exponential at low currents, a better method of measuring the quantity k was devised. This was desirable, since the graphical determination is both slow and inaccurate. The new method involved adjusting the voltage of the control element until the plate current read one microampere, and then applying a sine-wave alternating voltage from an adjustable potential divider and varying its magnitude until the plate current was increased to exactly two microamperes. If E_a is the peak value of the applied alternating voltage, k is given by

$$k = 1.81/E_a \tag{5}$$

The justification for this relation will be given later on.

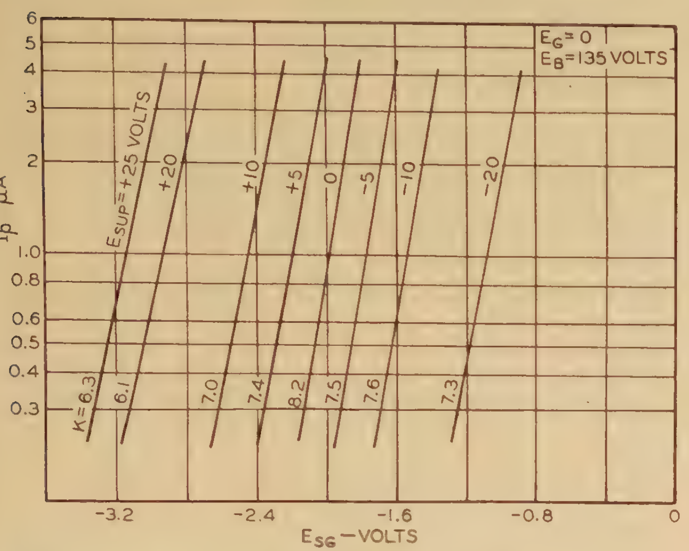


Figure 3. Effect of suppressor grid voltage on the plate current versus screen-grid voltage curves. Large positive voltages tend to reduce the slope

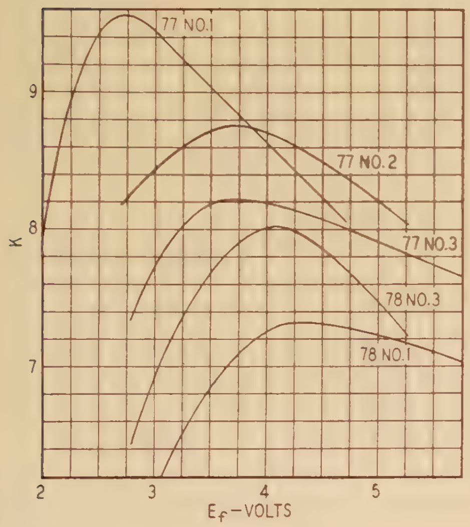


Figure 4. Variation of k with heater voltage for five different screen-grid tubes

The effect of heater voltage on the k of these same tubes was next studied, with results as shown in figure 4 for five different tubes. As the filament temperature is reduced, k increases, and this is as predicted by (2). However, if the filament temperature is dropped far enough, k must of course decrease, and would become zero when the emission stopped altogether.

If k is calculated from (2) for 1,120 degrees absolute, which is a typical operating temperature for oxide-coated cathodes,[2] a value of 10.37 is obtained. This is a little greater than the largest observed value of k, even though the latter occurred at a temperature below that of normal operation.

The values of k calculated from (2) for thoriated (2,000 degrees) and pure tungsten (2,550 degrees) cathodes are 5.80 and 4.55, respectively. Evidently oxide-cathode tubes are to be preferred for use in a slide-back voltmeter.

It was found that the voltage of number one grid had only a small effect on k over the range of +1.0 to −0.2 volts. However, negative biases of half a volt or more caused a large reduction in this parameter.

Table I

Type of tube	k
79—number 1	3.4
79—number 2	3.6
76—number 1	2.6
76—number 2	1.9
77*—number 1	2.7

* Number 1 grid and screen grid connected together as control element.

Table II

Type of tube	k
24—number 1	8.1
24—number 3	7.7
35—number 1	4.6
57—number 1	7.6
58—number 1	8.6

Values of k for Other Electrode Arrangements and for Other Tubes

As might be expected, a screen-grid tube showed a smaller value of k when the number one grid was used as the control element. This was true even with type 77 tubes, which cut off very much more quickly than do those having variable-mu structures. Thus, values of from 2.0 to 2.8 were found for 77's used in the normal manner.

A number of other tubes were also measured, with the results shown in table I. In all cases the plate voltage was 135 volts and the bias of the control element was adjusted to give an initial current of one microampere. Table II shows the values of k for several screen grid tubes of older types. The screen was used as the control element in each case, and the number one grid and suppressor, if any, were connected to the cathode. It is evident from these tables that tubes used with screen control give very much better values of k than do triodes, or pentodes used in the normal manner.

From the data which have been presented, it is clear that the operating voltages, with the exception of the heater voltage, of a pentode used with screen-grid control do not greatly affect the value of k. If the heater voltage is kept strictly constant, k is reasonably constant. Measurements taken at four different times during a period of a week, on three different type 77 tubes, showed a maximum variation of k with time, for any tube, of less than four per cent.

Rectification by an Exponential Conductor

If a sinusoidal voltage is applied to a device whose current-voltage curve is defined by (4), we have

$$I = G\epsilon^{-kE\cos\omega t} \tag{6}$$

The d-c component of this expression can be shown to be[4]

$$I = GI_0(kE) \tag{7}$$

in which $I_0(kE) = J_0(\sqrt{-1}\,kE)$. I_0 is the zero-order Bessel function of a pure imaginary argument. Values of I_0 are to be found tabulated on pages 277–82 of "Tables of Functions," by Jahnke and Emde, second edition, 1933.

As has already been explained, G can be adjusted to any desired value by means of an appropriate bias voltage. When the impressed alternating voltage is zero, $I_0(kE) = I_0(0) =$ unity. Suppose that the bias is so adjusted that $G = 1$ microampere when there is no impressed voltage wave. If, then, an alternating voltage is placed on the grid, the current in microamperes will be equal to $I_0(kE)$. If this impressed wave is adjusted to a value E_a, such that the d-c plate current is two microamperes, we have

$$I_0(kE_a) = 2 \tag{8}$$

From the tables we find that $I_0(x) = 2$ when $x = 1.81$. Hence, (5) follows immediately. It is to be remembered that E_a is the peak value of the impressed sinusoidal wave of voltage which will change the d-c plate current from an initial value of one microampere to twice that value.

When a sinusoidal voltage is to be measured with a slide-back voltmeter, the bias is first adjusted, in the absence of impressed voltage, until the plate current has a low, but readable value. If the grid bias corresponding to this condition is E_1, we have

$$I_1 = G\epsilon^{-kE_1} \tag{9}$$

The alternating voltage is then applied and the bias readjusted until the original current reading is restored. Then

$$I_1 = G\epsilon^{-kE_2}I_0(kE) \tag{10}$$

Table III

Peak Alternating Current	f(kE)	ΔE Calculated	E Measured
0.565	0.631	0.356	0.35
0.848	0.724	0.613	0.60
1.132	0.776	0.88	0.87
1.414	0.812	1.15	1.14
2.83	0.890	2.52	2.51
4.24	0.920	3.90	3.90
5.66	0.938	5.31	5.28
7.07	0.950	6.72	6.71
8.49	0.957	8.13	8.11
9.90	0.966	9.56	9.51
14.14	0.970	13.72	13.77
16.98	0.973	16.53	16.53
21.21	0.980	20.8	20.8

Let this difference between the two bias voltages $(E_2 - E_1)$ be ΔE. Then, equating (9) and (10) we get

$$\epsilon^{k\Delta E} = I_0(kE) \tag{11}$$

In the ordinary use of this type of voltmeter, it is assumed that $\Delta E = E$. Actually, this is not the case, and, in order to find the magnitude of the error, let us take the ratio of the two quantities. (11) gives

$$\frac{\Delta E}{E} = \frac{1}{kE}\log_\epsilon I_0(kE) = f(kE) \tag{12}$$

A plot of this ratio as a function of kE is shown in figure 5. In making computations for large values of kE, use was made of the formula[5]

$$I_0(x) = \frac{\epsilon^x}{\sqrt{2\pi x}} \tag{13}$$

which gives very accurate results for $x = 20$ and larger values.

This curve shows quite clearly that large errors may be made in measuring small voltages, and that these errors are the more serious if a tube with a small k is used. Actually, triodes have often been employed in slide-back voltmeters, and, as is indicated by table I, these tubes are likely to have values of k which are one-third to one-fourth as great as those which may be obtained with a pentode, using the screen as the control element. Thus, if we have a k of eight and a peak voltage of seven volts, the error in measurement will be five per cent (corresponding to $kE = 56$), whereas if k is only two, the error for the same applied peak voltage will be about 16 per cent.

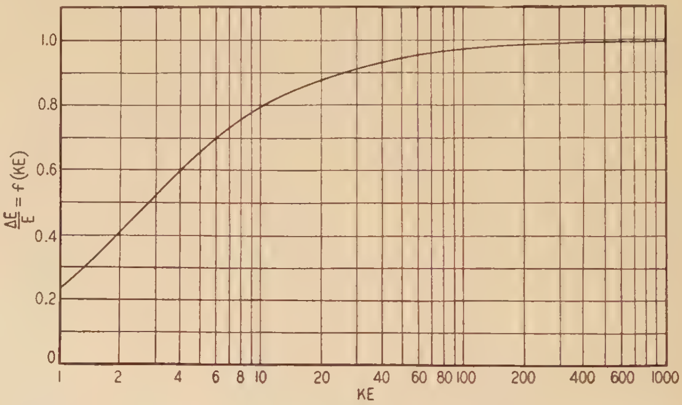


Figure 5. Ratio of apparent peak voltage ΔE to the true peak voltage E as a function of kE

A check of the validity of (12) is given by table III. In taking data for this table, an a-c source was adjusted to 15.0 volts root-mean-square by means of an accurate voltmeter, and a potential divider was used to obtain the smaller voltages. The value of $f(kE)$ corresponding to each peak voltage was determined from the curve of figure 5, and this, multiplied by the peak voltage, gives the value of ΔE which should result. The measured and calculated values are shown in table III.

The per cent correction is small for the higher voltages, but is quite large for peak values of a few volts or less. For the lowest voltage recorded, the error which would be made by omitting the correction factor would be 23 per cent of the impressed voltage. There is no reason why still smaller voltages could not be measured if sufficiently sensitive meters were used. When a slide-back voltmeter has been set up to measure large voltages, it often turns out that small ones must also be dealt with, and it is usually inconvenient to provide another voltmeter to handle them. The correction factor which has been developed makes this unnecessary.

In calculating table III, we have worked backwards from a known alternating voltage, and obtained the value of ΔE which should result. In practice, the alternating voltage will be unknown, and a correction must be applied to the observed ΔE. When k has been measured, it is a simple matter to plot a curve showing the relation between the observed ΔE and the peak value of the sinusoidal wave which is being measured, since the value of E corresponding to ΔE can be obtained directly from figure 5 as soon as k is known. A typical curve of E versus ΔE for $k = 8.2$ is shown in figure 6. Of course, this correction is accurate only if the voltage being measured is reasonably sinusoidal. It cannot be applied to nonsinusoidal waves, nor can a simple correction factor for measuring such waves be derived, for the ratio of ΔE to the true peak voltage would depend upon both the amplitudes and the phases of the harmonics, and these are usually unknown.

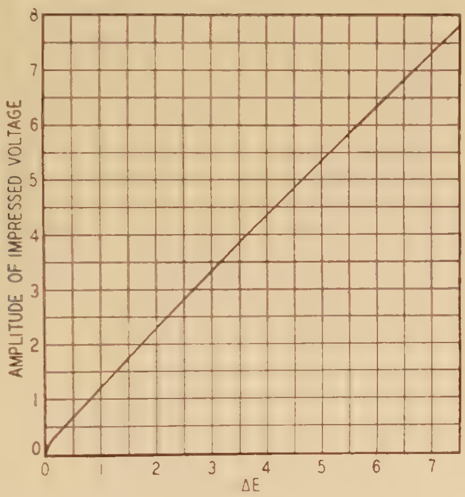


Figure 6. Calibration curve of a slide-back voltmeter derived from the curve of figure 5 for a value of k = 8.2

Circuit of the Slide-Back Voltmeter

Figure 7 shows the circuit of a slide-back voltmeter which is arranged for making measurements of k, as well as of unknown voltages. In order to measure k, the switch S is thrown into position 2, and resistance R_1 is adjusted until the voltage E_0 is equal to some reference value, say 50 volts peak. This value is determined by measurement with the slide-back voltmeter in the following manner. With the 60-cycle supply cut off, potentiometer P_3 is adjusted until the plate-current meter reads some small value, such as one or two microamperes, and the reading of voltmeter E_c is noted. P_3 is then increased by exactly 50 volts, the 60-cycle supply is switched on, and R_1 is adjusted until the plate current again reads the same as before. The voltage across R_2 and P_2 will then be 50 volts peak, except for the error inherent in a slide-back voltmeter, which we have been discussing in this paper. However, if a type-77 pentode tube is used in the voltmeter, it will have a value of k not far from 8, and hence kE will be about 400, and reference to figure 5 shows that the error will not be greater than one per cent. This can be eliminated if we use an increment in screen grid bias of 49.5 volts instead of 50 volts. Having adjusted the voltage across R_2 and P_2 to the proper value, the switch S is next thrown into position 3, and P_2 is adjusted until the plate current reads twice the no-signal value. Very small currents should, of course, be used. The value of k will be inversely proportional to the voltage across P_2, as shown by (5), and consequently the dial of P_2 may be calibrated to read k directly.

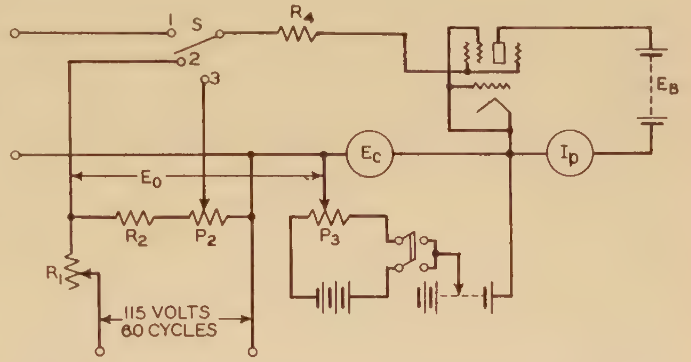


Figure 7. Circuit of a slide-back voltmeter with arrangements for measuring the value of k

When k has been measured, a curve such as that shown in figure 6 can be plotted with the help of figure 5, thereby calibrating the instrument. An unknown voltage is then measured by throwing the switch to position 1, short-circuiting the input terminals, and adjusting P_3 until the plate current is about one microampere. E_c is then increased to a value larger than the peak voltage to be measured, and the latter is applied to the input terminals. It is important to make E_c large enough in order to avoid damage to the plate-current meter. Next, P_3 is adjusted until the plate current is restored to its original value, and the increment in E_c is noted. This increment gives the peak of the voltage under measurement, by reference to the calibration curve.

R_4 is a high resistance of the order of 0.25 to 0.5 megohm, which will prevent the grid from going positive if the input voltage is accidentally allowed to exceed the bias voltage by any large amount. This furnishes some protection to the plate-circuit meter, but reasonable care will still be required to prevent damage to a sensitive instrument.

A plate voltage of 150 to 170 volts is satisfactory with type-77 tubes. If lower voltages are used, there is danger that the tube will draw grid current when a reading of one microampere plate-current is obtained, and this would lower the input impedance of the device. Moreover, if R_4 is in circuit, this would also introduce large errors in the measurements. If higher plate voltages are employed the maximum plate current which can occur during overload is increased, thereby adding unnecessarily to the ease with which the plate meter may be injured.

This voltmeter is simple and accurate, and greatly extends the range of usefulness of the slide-back type of instrument.

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2. Measurements in Radio Engineering, F. E. Terman. McGraw-Hill, page 28.

3. See, for instance, Phenomena in High-Frequency Systems, August Hund. McGraw-Hill, page 7.

4. Theory of Bessel Functions, G. N. Watson. Cambridge University Press, page 22.

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Discussion

C. F. Harding (Purdue University, Lafayette, Ind.): The unique method, described in this paper, in making possible the measurement of crest potentials with the slide-back voltmeter principle not only marks another important step in the varied application of standard electronic tubes but also provides a simple and fairly accurate device for determining these rather evasive values. It is readily used, in connection with a resistance or capacitance potentiometer, for determining the important crest values of sustained wave forms in the extra-high-potential laboratory.

However, this combination with the slide-back voltmeter, requiring as it does two readings for every potential determination, is not applicable to steep-front surges nor to nonrepetitive wave shapes. It is hoped that, as the result of this study, the electronic tube, which seems to be well adapted to such control, may be soon adapted to the measurement of the individual crest values of surges of the order of one microsecond duration or less with a single reading and that ultimately such may be reduced down to cgs units to provide the much-desired primary standards for extra-high-potential measurements. Unfortunately, in spite of the long and careful experimentation and consideration of the committee on high-voltage standards, nothing better than the sphere gap has been developed for surge potential measurement. This gap has many disadvantages and, furthermore, is not a primary standard. It is hoped that this paper may act as a possible solution and a valuable progress report looking toward that important selection of such a primary standard.

C. B. Aiken and **L. C. Birdsall**: As Doctor Harding points out, the slide-back voltmeter is not, of course, applicable to nonrepetitive wave forms, nor is the correction derived in this paper applicable to repeated waves that are markedly nonsinusoidal. However, the diode rectifier can undoubtedly be adapted, with the help of auxiliary apparatus, to the measurement of transient voltages in which the maximum value of dE/dt is not too great, the limit being determined largely by irreducible stray capacitances in the measuring circuits. It would require a special investigation to determine just how useful a diode voltmeter can be made for surge measurements, but it is believed that an advance over present equipment would be possible. In any such investigation, advantage could be taken of the exponential nature of the diode characteristic in working out a quantitative theory of operation.

Interpretation of Oscillograms of Arc-Welding Generators in Terms of Welding Performance

By K. L. HANSEN
FELLOW AIEE

IT HAS long been recognized that the transient performance of an arc-welding generator greatly exceeds its static performance in importance. By transient performance is meant the behavior of the machine during the period of readjustment after a disturbance has taken place in the external circuit. Unlike most generators, an arc-welding generator supplies energy to a load in which conditions are continually changing, and the importance of the machine's ability to respond quickly to these rapid variations is obvious.

In the literature on arc-welding generators can be found many discussions on the static, or steady-state volt-ampere curve. The static volt-ampere curve is obtained by taking readings of voltage and current when the external load resistance is varied in suitable steps from infinite value on open circuit to approximately zero value on short circuit. Sufficient time is taken on each step of resistance to allow the current and voltage to settle to steady values before readings are taken; in other words, it is a characteristic volt-ampere curve for a slowly varying resistance only. Many arguments have been advanced for a certain shape or a particular degree of steepness of the static volt-ampere curve.

The volt-ampere characteristic of the arc when plotted with volts as ordinates and amperes as abscissas is a line approximately parallel with the horizontal base line. From this it is inferred that a steep volt-ampere characteristic of the welding system, which crosses the arc characteristic in such a manner as to make a large angle at the intersection, will be conducive to arc stability. However, with the possible exception of the constant potential welding generator with negligible inductance in the arc circuit, the relation between voltage and current indicated by the static volt-ampere curve never prevails under actual welding conditions. For that reason it is not the steepness of the static volt-ampere curve which is the principal factor in determining arc stability, but the steepness of the transient or dynamic volt-ampere curves. Yet the writer has never observed any discussion on the shape or steepness of the much more important transient or dynamic volt-ampere curves.

Figure 1 shows an oscillogram of the arc voltage and current which may be considered typical, the generator and the covered electrode used both being standard commercial articles. An automatic head was employed to feed the electrode. The voltage drops to zero as the drops of molten metal short-circuit the arc at more or less regular intervals. Whenever the drops short-circuit the arc the familiar momentary rise of current can be observed. However, even between drops the current and voltage fluctuate continually and never reach steady values. The voltage fluctuations are especially pronounced. Unlike the steady resistance load employed in taking the static volt-ampere curve, the resistance of the welding arc constantly undergoes rapid and wide variations.

When the metal is transferred across the arc in the form of fine pellets instead of drops, the periodic reduction in the arc voltage may not be so pronounced. But even in that case there is a noticeable variation in the arc resistance, as the stream of pellets is apparently not uniform but takes place in gushes. It has been generally assumed that with a coated weld rod the metal is transferred in a more finely divided state than when a bare rod is used.

However, the degree of comminution of the molten metal appears to depend on the magnitude of the current rather than the coating. When using a current which is large for the size of the rod the fluctuations of voltage and current are greatly minimized with either a coated or a bare weld rod. With the current densities usually employed, the voltage fluctuations are substantially as shown in figure 1 and they may be considered typical.

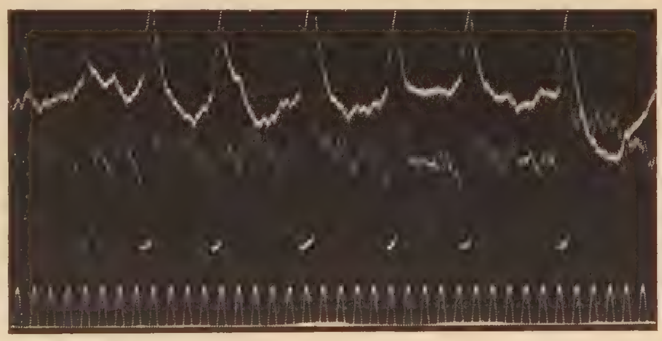

Figure 1. Oscillogram of arc current and voltage; approximately 200 amperes, 30 volts

The current fluctuations attendant upon the short circuiting of the arc have been subject to considerable discussion. Some maintain that they are detrimental in that they increase spatter and lower the deposition efficiency, and may even cause porosity. Others claim that they improve the penetration and are therefore de-

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1. For all numbered references, see list at end of paper.

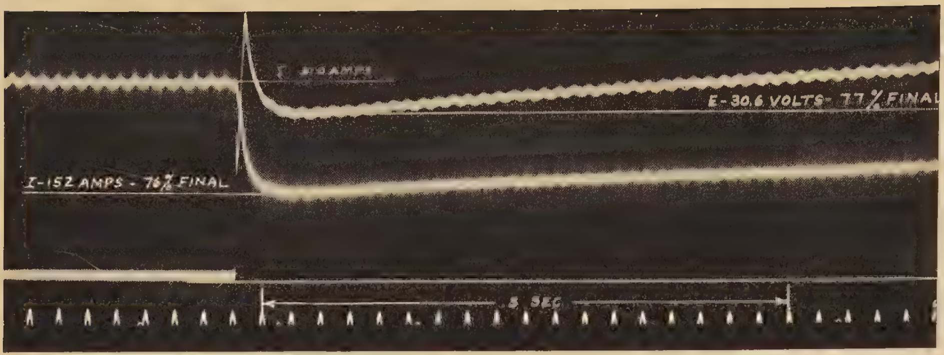
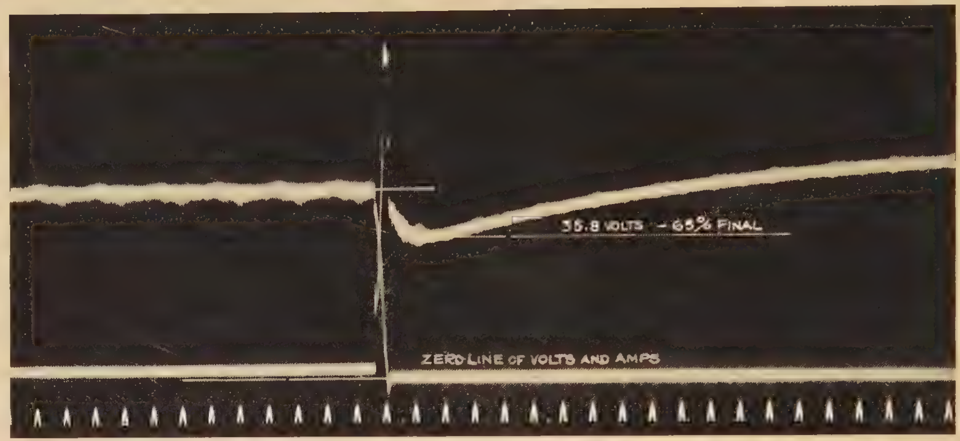


Figure 2. Oscillogram of current and voltage on short to load test on 200-ampere welding generator set at 200 amperes, 40 volts

Figure 3 (below). Oscillogram of voltage on short to open circuit test on 200-ampere welding generator



sirable. Although it is improbable that the penetration is improved by these fluctuations, strange as it may seem, there is something to be said for each of these contradictory claims.

It should be understood that there are two sources of current fluctuation when the arc is short circuited. The current may increase because the permanent short-circuit current on the volt-ampere characteristic is considerably higher than the current at welding voltage. The current increase may also be produced by a transient overshoot, which will be large if the transient characteristic of the machine is poor. It is the former type of fluctuations which is the subject of this discussion, as no one will claim any advantage for the latter type.

It is not likely that any great benefit is derived from these fluctuations in producing better penetration. Since the first draft of this manuscript was submitted, an article has appeared which completely verifies this intuitive statement.[1] However, they do serve a useful function, which will be discussed later, but they must be kept within certain limits or they become harmful.

It is generally agreed that oscillograms of arc current and voltage when welding are useful in comparing the performance of two machines if they can be tested under identical conditions. However, they are not well adapted to serve as a basis for specifications to cover the transient performance of a welding generator. To answer this purpose the test must be of such nature that it can be duplicated anywhere under certain prescribed conditions.

Inadequacy of Present Specifications

It is natural that specifications which have so far been formulated to cover tests for transient performance of welding generators should simulate as far as possible the conditions prevailing in the arc. That is, oscillograms are taken of the current while the external resistance undergoes a prescribed variation. For example, the AIEE test of a welding generator for momentary current fluctuations and arc recovery is as follows.

Adjust generator on resistance load to obtain normal current at 25 volts. Short-circuit one half the resistance and allow current to settle. Then suddenly open the short circuit and reinsert the resistance in the circuit. The current momentarily drops below normal and the time of recovery is the time required for the current to return to within five per cent of its original value. The resistance variation prescribed by this specification is so narrow as to preclude its being of any use.

Another specification for arc recovery states that the machine should be loaded on a resistance to give 40 volts across the resistance and a current corresponding to the setting at which the test is made. The entire resistance is then short-circuited and the conditions allowed to become stable. The short circuit is then suddenly opened, reinserting the resistance. The momentary current drop should not fall below 70 per cent of normal and the current should be back to within five per cent of normal in not more than 0.3 second.

Figure 2 shows an oscillogram made according to this test on a 200-ampere machine at full load.

This test is an improvement on the AIEE specification in so far as the prescribed resistance variation is wide enough to produce an appreciable current fluctuation. However, the usual interpretation of this test leaves much to be desired. Experience has shown that a machine which meets this specification may be definitely inferior to one which does not, and vice versa. The requirement that the current should return to within five per cent of normal in not more than 0.3 second is a particularly valueless stipulation, inasmuch as the disturbances in the arc occur at much shorter intervals than 0.3 second. What happens on a test of this kind after, say 0.1 second, is of no interest. This test unquestionably has some merit, but it is felt that it may be interpreted in a manner to give it greater usefulness than has so far been the case.

In addition to specifications for current recovery, there is at present in existence a specification for voltage recovery. It states that when a machine is suddenly open circuited from short circuit the time of voltage recovery is the time required for the voltage to reach 50 per cent of normal open-circuit voltage. Figure 3 shows an oscillogram of voltage recovery from short circuit. The test itself is valuable and gives more information about the transient performance of the machine than the other tests discussed, but the definition of voltage recovery given above is absolutely valueless.

It will be observed that the voltage rises quickly to a high value, then drops to a comparatively low value, from which it gradually recovers to normal. The rapidity with which the first rise of voltage takes place depends entirely upon the rapidity of the break of the current. This is the voltage induced by the rapid change of current in an inductance and it will be instantaneous if no arc is formed at the break, or if means are employed to blow out the arc if one is formed. In general, this voltage rise reaches a maximum when the current reaches zero, and the time required to reach this maximum is of no value as a criterion of performance of the machine, but its magnitude is of great importance. The peak value of this first voltage rise should always be considerably higher than the normal open-circuit voltage, and if the time required to reach this peak is of no importance, the time required to reach 50 per cent of normal can certainly have no significance.

The minimum value to which the voltage drops after the first sudden rise is an indication of the building-up characteristic of the fields. The higher this value is maintained, the faster the fields build up to produce a sustained voltage. As before, the gradual increase in voltage after this minimum voltage is passed is of little significance. It is the magnitudes of the maximum and minimum voltages on this test that are of importance. They are indications of the machine's ability to react quickly to sudden current changes by virtue of an appreciable amount of inductance in the circuit, and also the ability of the field to build up rapidly enough to sustain the voltage after the quick change has taken place. It will be shown later how this test, taken in conjunction with the previously discussed load test, can be interpreted to give a clear picture of the entire transient performance.

A Prerequisite for Arc Stability

Experience gained from many years of operation of constant-potential welding generators furnishes a clue to the reason for failure of the current-recovery test described above to tell the whole story. On a test of this kind the constant potential machine, where the drooping volt-ampere curve is produced by inserting resistance in series with the arc, will show 100 per cent current recovery. It shows no overshoots or under-rides on the recovery test.

Likewise, on the voltage-recovery test, the constant potential machine will show instant recovery to full open-circuit voltage. This, of course, is evident. Yet, experience showed that a variable voltage machine in which the drooping volt-ampere characteristic is produced by magnetic means frequently performed better on actual welding, even though it has considerable overshoots and under-rides on the current-

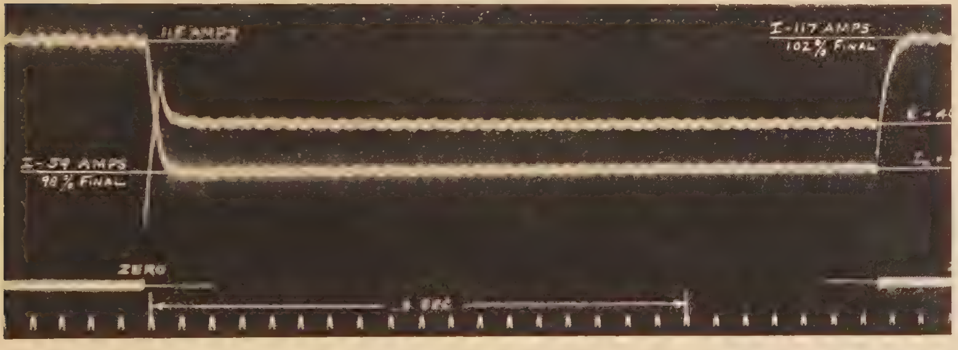


Figure 4 (above). Oscillogram of current and voltage on short to load test on 200-ampere welding generator set; 60 amperes, 40 volts

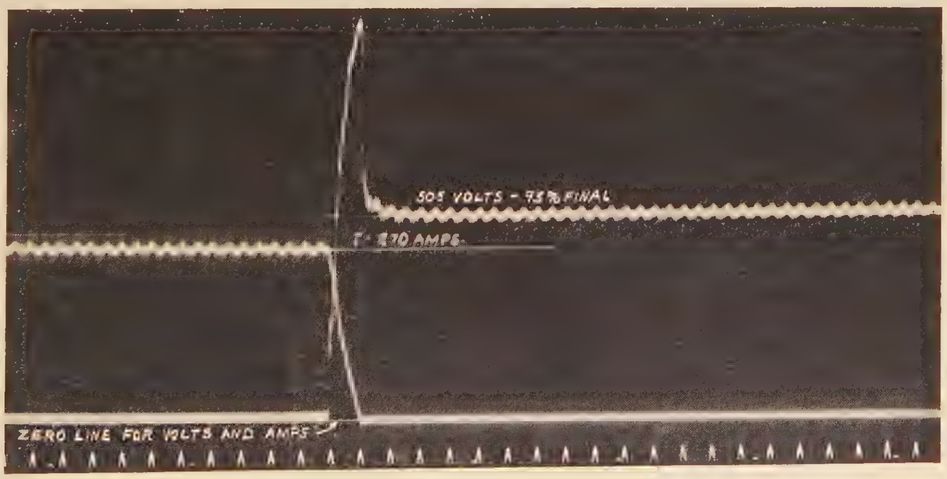


Figure 5. Oscillogram of voltage on short to open test on 200-ampere welding generator

recovery test. Furthermore, experience also showed that the operation of the constant potential machine was markedly improved by insertion of a certain amount of inductance in the circuit, especially if the volt-ampere characteristic is fairly flat.

Figure 4 shows an oscillogram of a current-recovery test on a 200-ampere machine with sufficient resistance in the circuit to give it the constant potential characteristic. However, it is also supplied with an inductive stabilizer. It will be observed that the current drops from the short-circuit current to normal with practically no dip. Without the inductive stabilizer in the circuit, substantially the same current-recovery curve would be obtained. However, the insertion of the inductance modifies the voltage curve very materially. Without the inductance the voltage would rise quickly to normal and stay there. With the inductance in the circuit the voltage rises rapidly to a value considerably above normal before settling down. This overshoot of voltage when there is a sudden reduction in current is apparently of great benefit in stabilizing the arc.

Similar phenomena will also be observed on the voltage recovery test on the same machine shown in figure 5. Without the inductance the voltage would rise to the normal open-circuit voltage without overshoot. With the inductance, a higher voltage peak is obtained.

These observations merely verify the familiar fact that the more electromagnetic energy there is stored in an electric circuit, the greater is the tendency to establish an arc when the circuit is broken. When a drop of metal forms a short circuit the arc is extinguished and the high instantaneous voltage induced when there is a sudden reduction in current is a direct measure of the tendency to re-establish the arc upon the reopening of the arc gap. The minimum sustained voltage is a measure of the tendency to maintain the arc once it has been established. The importance of the magnitudes of these voltages can, therefore, readily be appreciated.

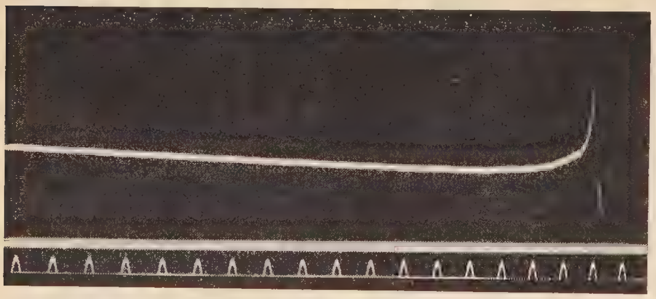


Figure 6. Oscillogram of voltage on short to load test on 400-ampere welding generator set at 400 amperes, 40 volts

Long experience with another type of equipment points in the same direction. In endeavoring to apply a-c current to arc welding it was soon discovered that a drooping volt-ampere characteristic produced by resistance in series with the arc, similar to the constant-potential d-c system, was of practically no value in bringing about arc stability. On the other hand, when the drooping volt-ampere characteristic was produced by reactance in either primary or secondary circuit, the arc stability was greatly enhanced.

With resistance in the circuit, the power factor is high, and the secondary voltage and current rise and fall practically in unison. When the current passes through the zero point the arc goes out and the voltage rise following an approximate sine wave is too slow to re-establish the arc, and it stays out. With reactance in the circuit the power factor on the input side is low and on the output side the voltage wave is distorted into an almost rectangular shape, frequently with a sharp peak on the leading side of the rectangle. This abrupt rise of voltage immediately after the current passes through the zero point is an essential requirement to quickly and surely reignite the arc. The inference from experience, therefore, is that whenever the arc has gone out for any reason, such as being short-circuited by a drop of metal in d-c welding or the current passing through zero in a-c welding, a rapid rise of voltage to a relatively high value, even if of short duration, is a necessary requisite for the reignition of the arc, and therefore highly desirable.

The theory of the arc, as it has been developed so far, appears to agree with experience. According to Doctor C. G. Suits,[2] the resistance of the arc depends on the state of ionization of the gaseous medium, which in turn depends on the ionizing voltage and the temperature. Furthermore, the ionization follows a variation in the temperature almost without time lag, the period of readjustment being of the order of 0.001 second. The short circuiting of the arc by a drop of metal and the consequent momentary extinction of the arc is unquestionably followed by a drop in temperature of the surrounding gases.

The initial resistance of the arc upon the reopening of the arc gap as the drop leaves the electrode is, therefore, considerably higher than the average arc resistance. A rapid and relatively high voltage rise at that instant is then effective in reducing the initial resistance by rapidly increasing the state of ionization of the arc gases. The failure of the current-recovery test, as interpreted at present, to give a correct picture of the transient performance, is undoubtedly due to the fact that it does not take into account the variation in arc resistance with temperature and applied voltage. To give this test the maximum of usefulness, the voltage fluctuations which take place when the test is made should also be taken in consideration.

Transient or Dynamic Volt-Ampere Curves

As the maximum and minimum voltages induced when there is a sudden interruption of the circuit, or a sudden insertion of a resistance in the circuit, are determining factors in producing arc stability during welding, these values plotted in the form of curves similar to the static volt-ampere curves should prove of interest. The open-circuit points for these curves are obtained from the voltage-recovery test already described. The load points are obtained by tests similar to the current-recovery tests, except that oscillograph records are made of the voltage only. The machine is loaded on resistance, which gives a point on the static volt-ampere curve. The resistance is then short-circuited and conditions allowed to become stable. The resistance is then suddenly opened and a record made of the maximum and minimum voltages, as shown in figure 6. In making this test the film should travel fast to obtain a distinct maximum voltage point, also the short should be interrupted quickly. If necessary, a blowout of the arc should be provided. The resistance is then varied in suitable steps and the test repeated.

Figure 7 shows the static and transient volt-ampere curves for approximately full load setting of a 400-ampere welder. The curves give a clear picture of what happens when a resistance is suddenly inserted from a short circuit. While the current drops quickly from the steady short-circuit value, the voltage rises quickly along curve 2, reaching point *A* approximately at the time the current has dropped back to normal. From this point on the current drops slowly. The voltage at first drops quickly along *ab* until the current and voltage simultaneously reach their minimum values at *B*. From there on they increase rather slowly along *bc* to *C*. As pointed out, this gradual approach back to normal is of no significance. The point *B* can readily be determined from the fact that the percentage reduction in current is substantially equal to the percentage in voltage below normal. This eliminates the necessity for recording the current with the oscillograph and simplifies the operation considerably.

Curve 1—Transient volt-ampere curve of momentary short-circuit current values

Curve 2—Volt-ampere curve of transient peak voltages obtained during change from short-circuit condition to a resistance load condition

Curve 3—Volt-ampere curve of static or steady-state conditions obtained by various resistance loads

Curve 4—Volt-ampere curve of minimum voltage obtained when changing from short-circuit condition to a given resistance load condition

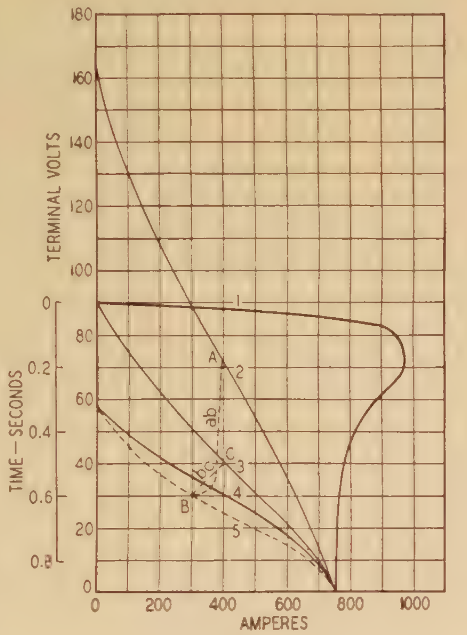


Figure 7. Transient and static (steady-state) volt-ampere characteristics of 400-ampere welding generator

It can readily be seen that the steady short-circuit current must be appreciably higher than the welding current in order to induce a high substantially instantaneous voltage when a resistance is suddenly inserted in the circuit. On the other hand, it is desirable to keep the current fluctuation from becoming excessive when a sudden short takes place. Recent tests have shown that large short-circuit currents tend to produce weld metal of large grain size with poor impact value and greatly increased spatter loss. For convenience, the record of the current when the machine is suddenly shorted from open circuit may be plotted on the same sheet as shown by curve 1. The overshoot is in this case higher than it would be if the short was made from a resistance load at lower voltage, but it represents the possible maximum current fluctuation and is, therefore sufficient.

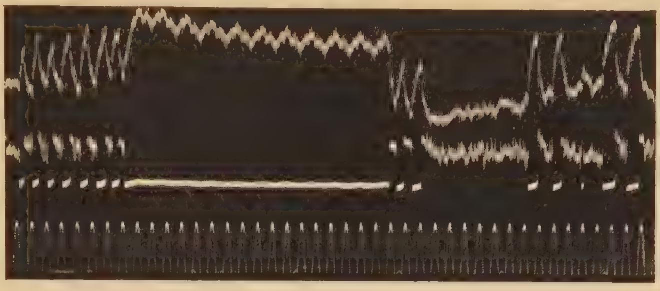


Figure 8. Oscillogram of arc current and voltage when welding with three-sixteenths-inch bare electrode. Approximately 160 amperes, 20 volts

The degrees of steepness of curves 2 and 5 are the important factors in determining arc stability. Of course, the degree of steepness has no meaning unless the scales of co-ordinates are agreed upon. However, the ratio of volts to excess of short-circuit current over normal current may be taken as the measure of steepness. For example, the curves in figure 7 were taken at 400 amperes, 40-volt setting. At 400 amperes curve 2 shows a voltage of 72 volts; 72 divided by (760 − 400 = 360 amperes) = 0.2. In the same manner the steepness factor of curve 5 is 0.0695.

A moderately steep static volt-ampere curve together with a much steeper curve 2 produces a very desirable characteristic. The steepness of curve 2 is very effective in producing arc stability provided the arc length is kept within certain limits. At the same time, the moderate steepness of curve 3 precludes an excessively long arc. In many applications the operators have to break the arc frequently and they prefer a clean break when the arc is drawn beyond a certain length, but they also desire the arc to hang on tenaciously within that length. A wide spread between curves 2 and 3 is conducive to this desirable feature.

It is interesting to observe the voltage peaks resulting from a rapidly decreasing current when welding with a machine with good transient characteristics. Figure 8 shows these peaks distinctly and is especially interesting as the operator happened to short-circuit the arc when the film was taken. The sharp voltage rise after each short circuit as the drops go across is indeed the most important criterion in judging the transient performance of a welding generator from an oscillogram taken while welding.

Bibliography

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2. High Pressure Arc, C. G. Suits. *General Electric Review*, April 1936.

Discussion

R. C. Freeman (nonmember; General Electric Company, Schenectady, N. Y.): The article shows two important features of the voltage-recovery characteristics of a d-c power source for arc welding, graphically represented on the basis of the same voltage ordinates and current abscissas as are used for the static volt-ampere curves.

The prime importance of various recovery characteristics has long been recognized by those acquainted with the design and operation of arc-welding generators. There has been much discussion as to the relative importance of the different features of voltage and current recovery under variously specified conditions. From the extensive experience of many engineers there has developed the consensus that peak-voltage recovery, or certainly the constants indicated by the presence of such a voltage surge, and minimum voltage recovery are two of the most significant phases of the transient phenomena.

The transient characteristics of a welding generator as graphically represented in figure 7 of the article, would become more meaningful if the time element were evaluated. This is particularly true in curve 2 of figure 7 which is a plot of transient peak-voltage values. Since this peak voltage is an electromotive force induced by the rapid change of current when a short circuit of the generator is completely opened or opened across some predetermined resistance, this value then is a function not only of the constants of the welding generator but also of the speed of opening of the short circuit. Significant though such peak values are, they do not lend themselves to a simple and accurate quantitative determination of the welding-generator constants which are necessary for the maintenance of a good welding arc.

The author minimizes the significance of the time element in the ultimate recovery and current to steady-state values. Although the magnitude of minimum voltage recovery is of much more importance in the maintenance of an arc, yet it is also true that the time required for the current in the arc to recover to a normal value (that is, the time required for the transition from point *B* on curve 5 to point *C* on curve 3 of figure 7 of the article) is worthy of consideration as a means of obtaining more uniform welding performance. It is noteworthy that in the ultimate recovery of current and voltage (to point *C*, figure 7) from the minimum value (point *B*, figure 7) there is an increase of 75 per cent in the watts of electrical energy delivered to the arc. Obviously it is advantageous to complete a transition of such proportion in a minimum period of time.

In a time where there are so many conclusions drawn and claims made regarding welding performances which are based upon only a superficial consideration of static volt-ampere curves, this article stands for a true analysis of arc welding performance based upon the all-important consideration of transient characteristics.

K. L. Hansen: The maximum and minimum voltages following the sudden insertion of a resistance in the circuit are apparently recognized as the most important criteria in judging the welding performance of a generator. However, Mr. Freeman is skeptical about the ability to determine the peak voltages readily and with a reasonable degree of accuracy. He is of the opinion that the magnitude of the voltage peak is materially influenced by the time element involved in breaking the circuit.

It is true that the time required for the voltage to reach its maximum value on the short-circuit-to-open-circuit test is directly dependent on the rapidity of the break. In general, the voltage reaches the peak when the current has dropped to zero, as stated in the paper. But, strange as it may seem, the magnitude of the voltage peak is by no means inversely proportional to the time required for the current to reach zero, although it is considered to be induced principally by this rate of current change. This point was brought out rather forcibly by a test made some years ago.

In discussing my paper ("Recent Developments in Design of Arc Welding Generators," AIEE Transactions, June 1932, page 576), Mr. Ver Planck contended that a "slow" break would assist the generator in maintaining a high minimum sustained voltage in so far as it gave the generator fields more time to build up. He compared the oscillogram of a recovery test shown in my paper with one taken on a Bergman machine and found that the short circuit was interrupted six times more slowly on the Hansen machine. This, Mr. Ver Planck claimed, assisted the Hansen machine in showing a high "minimum recovery" voltage.

This point was carefully checked by repeating the test on the Hansen machine and taking special precaution to break the arc quickly. The rate of breaking the current was speeded up to compare with the test on the Bergman machine, that is, about six times faster than on the recovery test shown in the paper. In spite of the greatly increased rate of current change, the peak voltage was only about 30 per cent higher and the minimum recovery voltage, instead of being lower as Mr. Ver Planck expected, was a few volts higher. Here a greatly increased rate of current change produced only a moderate change in the peak value of the voltage and a very slight change in the minimum value. It is their comparative freedom from dependence upon the rate of interruption that led me to propose the consideration of the magnitudes of the peak and minimum voltages on the recovery tests rather than the ridiculous stipulation of "the time required to reach 50 per cent of normal voltage."

When the short circuit is opened on a predetermined resistance the importance of the time element in affecting the magnitude of the voltages is less than when the circuit is completely opened, and the lower the value of the resistance on which it is opened the less important the time element becomes. The tendency to form an arc when a circuit is opened is greatly minimized when a circuit of low resistance is connected in parallel with it.

Possible errors in the peak-voltage values due to variation in the rate of interruption, therefore, become progressively smaller for lower points on curve 2. That is fortunate because it is the steepness of this curve over the welding range that is of importance. What happens as the curve approaches the open-circuit point is not of much consequence. The fact that the peak values come out on a smooth curve is an indication that they cannot be very erratic. It is certainly easier to determine the voltage peaks than the gradual approach to within five per cent of normal current on the present current recovery test.

Mr. Freeman's second criticism that little consideration is given in the paper to the time of current recovery deserves to be commented on. Mr. Freeman states that there is an increase of 75 per cent in the energy delivered to the arc as the current and voltage pass from their minimum values to normal.

This statement is evidently based on the assumption that the behavior of the current and voltage is the same when a fixed resistance is inserted in the circuit as it is when the arc gap is opened due to a drop leaving the electrode. This, however, is far from being the case, as pointed out in the paper. A close study of many oscillograms taken during actual welding operations has not disclosed any tendency for the current and voltage to start at low values and gradually approach normal after recovering from a short circuit caused by a drop. Even when there is no drop passing across for as many as 10 to 12 cycles there is no evidence of such a tendency. The reason probably is that the conductance of the arc is itself a function of the applied voltage. A high peak value of voltage following immediately upon the opening of the short circuit appears to establish normal current flow quicker in the arc than it does in a fixed resistance. This is the reason that so little consideration is given in the paper to the time of current recovery when it is taken on a resistance.

Co-ordination of Power Transformers for Steep-Front Impulse Waves

By V. M. MONTSINGER
FELLOW AIEE

Introduction

THE REQUIREMENT that transformers withstand certain specified impulse tests has been accepted by the industry as desirable, and the Institute has recommended a standard method of testing transformers with a 1.5 x 40 microsecond wave.

These tests, however, do not demonstrate that transformers can withstand steep-front waves when the voltage is limited by flashover of their bushings or of rod gaps that give ample protection for long waves. The reason, of course, for this is that the flashover voltage of an air gap increases faster than the breakdown voltage of insulation as the time (to flashover or breakdown) gets shorter. This means that the margin of safety of the transformer, when protected by an air gap, decreases as the impulse wave front becomes steeper and for very steep fronts the margin may disappear. It is now generally recognized that to protect a transformer by an air gap against steep front waves, the spacing of the gap must be much lower than that necessary to protect against long waves.

Furthermore, in cases where transformer windings have an inherently poor initial impulse voltage distribution at the line end, the steep-front waves produce steeper gradients (in per cent of the applied wave) than are produced by long waves with the result that breakdown may occur between the turns and coils, before the major insulation fails. This is particularly true of the higher-voltage unshielded windings. In such cases shorter air gaps may be required to protect the line end coils than are required to protect the major insulation.

Though greatly improved in impulse strength, within the past few years, it has to be admitted that modern high voltage transformers cannot withstand the kilovolts associated with excessive steep-front lightning waves resulting from direct strokes on or near its terminals. The major insulation would fail. Transformers, of course, could be built to withstand direct strokes but this cannot be economically justified. Extremely steep-front waves should, of course, be kept out of the station by suitable means and suitable protective devices used for protection against dangerous incoming traveling waves.

Finally, to co-ordinate or protect transformers intelligently for all kinds of impulse waves requires an accurate knowledge of the volt-time characteristics of transformer insulations. Data of this kind can be determined only by careful laboratory investigations of typical transformer insulations. Such investigations have been under way during the past few years.

Purposes of Paper

The purpose of this paper is to report the results of these laboratory tests made to determine the impulse volt-time curve characteristics of transformer insulations, based upon the effect of both single and repeated applications of impulse voltages on both the corona injury level and the breakdown. Front-of-wave testing of transformers is also discussed.

A. Volt-Time Characteristics of Transformer Insulations

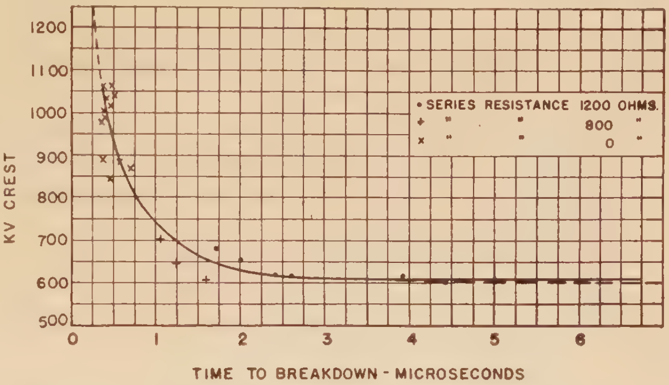

Figure 1. Single-shot volt-time curve of barrier A (36 inches by 48 inches). One-quarter inch oil plus one-eighth inch P. B. plus one-quarter inch oil plus one-eighth inch P. B. plus one-quarter inch oil—total thickness one inch; four-inch-diameter square-edged electrodes; 1.5 x 40 negative wave

Considerable data have already been published[1–4] on volt-time curves of solid insulation, on transformer oil and on solid insulation in series with oil (representing the major insulation in a transformer). Most of these curves were based upon breakdown caused by a single application of voltage for the various "times to breakdown." Unlike an air gap, insulation has the characteristic of being weakened by repeated applications of voltage above the injury level. Therefore, in comparing the volt-time curve of transformer windings with air gaps, it is quite necessary to use insulation curves based upon repeated voltage applications for the reason that we have no assurance that a transformer will not be subjected to more than one lightning stroke. In fact, it has been shown[5] that in a (supposedly) single stroke a large number of impulses may

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[1] For all numbered references, see list at end of paper.

follow each other in rapid succession. Another reason why co-ordination and protection should be based upon the "repeated impulse wave" volt-time curves of insulation is that the application of a single wave having an amplitude higher than the repeated wave strength will cause injury even though failure does not occur.

Insulation Barriers

Tests were made on four different barriers designated as *A*, *B*, *C*, and *D*, designed to simulate the major insulation in transformers. Barriers A and B in all cases had bare electrodes. Barriers *C* and *D* had insulated line (generator-side) electrodes and a flat metal sheet for ground electrodes.

Tests on Barriers *A* and *B*

Barrier *A* consisted of one-fourth inch oil, one-eighth inch pressboard, one-fourth inch oil, one-eighth inch pressboard, and one-fourth inch oil—total thickness of barrier of one inch. Barrier *B* was the same as *A* except that it consisted of one-eighth inch oil ducts and one-sixteenth inch pressboard sheets—total thickness one-half inch. In all cases the oil ducts were maintained by two spacing strips one-half inch in width under the electrodes.

(*1*). *Single-Shot Breakdown Volt-Time Curves.* Figures 1 and 2 give the results of tests made on barriers *A* and *B* to obtain volt-time curves based on single-shot breakdowns with a negative 1.5x40 microsecond wave. The line and ground electrodes were four inch diameter disks with square edges.

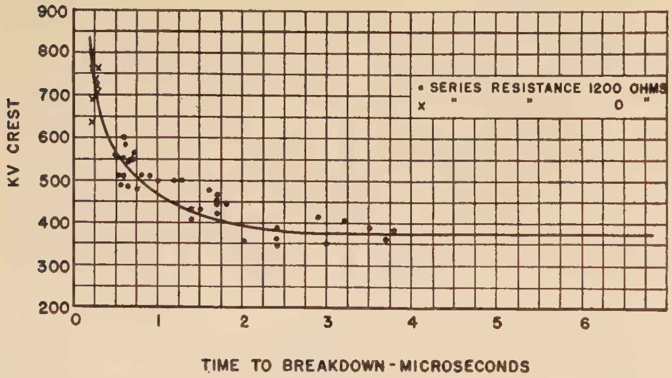


Figure 2. Single-shot volt-time curve of barrier B (36 inches by 48 inches). One-eighth inch oil plus one-sixteenth inch P. B. plus one-eighth inch oil plus one-sixteenth inch P. B. plus one-eighth inch oil—total thickness one-half inch; four inch diameter square-edged elecrodes; 1.5x40 negative wave

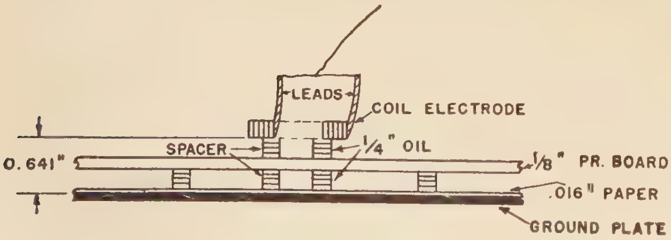
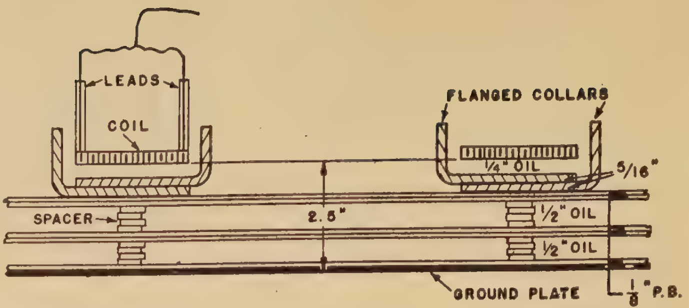


Figure 3. Insulation barrier C used for dielectric tests



BARRIER PARTS	BARRIER C	BARRIER D
COIL CONDUCTOR	.300 X .120"	.300 X .100"
COIL INS. (ONE SIDE)	(.006" PAPER (.003" COTTON	(.138" PAPER (.003" COTTON
COIL DIAMETER (INSIDE)	4.0"	9.25"
COIL RADIAL BUILD	1.875"	1.875"
SIZE OF PRESSBOARD	36 X 48"	36 X 48"
SIZE OF GROUND PLATE	36 X 48"	36 X 48"

Figure 4. Insulation barrier D used for dielectric tests

Expressed in percentages of kilovolts versus time to breakdown the curves in figures 1 and 2 give the values shown in table I.

(*2*). *Life Tests With Full Waves.* To obtain the effect of repeated shots on the breakdown strength as compared with the single-shot strength with a 1.5 x 40 wave, several thousand shots (covering a period of about one year) were made on barriers of type *A*. Three shapes of line electrodes were tried out, these being (1) four-inch-diameter square edge; (2) rectangular U-shaped rods; and (3) one inch round U-shaped rods. The rectangular and round rods were well rounded at the bends. The ground electrode was a metal sheet 36 inches by 48 inches.

The only definite conclusions that could be drawn from these life tests were, first, that on repeated shots the "wait" between shots apparently had no effect on the final breakdown value. In other words, there appears to be no heating effect with impulse voltages as occurs with low frequency voltage.[6]

Second, the breakdown value was reduced (below the single-shot value) quite rapidly on the first few shots, approximately 50 per cent of the reduction occurring in the first ten shots and then decreasing to the final or minimum breakdown value in the next 25 or 50 shots.

No dependable curve of breakdown versus number of shots could be obtained for the reason that injurious corona in some cases started as low as 60 to 65 per cent of the single-shot breakdown value, but failure did not usually occur (under many shots) until approximately 90 per cent of the single-shot breakdown value was reached. Obviously, when the insulation was tracked near the line electrode at 65 to 75 per cent voltage the final breakdown value of approximately 90 per cent voltage did not mean anything. Apparently dependable life tests cannot be obtained with bare line electrodes. This, of course, is not a practical condition as all transformer conductors are insulated.

Tests on Barriers *C* and *D*

At this point it was decided to use insulated line electrodes or small coils with barriers, designated previously as *C* and *D*.

Table I. Impulse Volt-Time Values by Test

Time to Breakdown (Microseconds)	Kilovolts in Per Cent of Full-Wave Kilovolts
0.25	200
0.5	150
1.0	125
1.5	113
2.0	105
Full wave	100

Barrier *C* consisted of a small coil as the line electrode and a plane as the ground electrode, the two electrodes being separated 0.641 inch consisting of one-fourth inch oil, one-eighth inch pressboard, one-fourth inch oil, and a 0.016 inch sheet of paper adjacent to the ground plate. See figure 3. The turns in the coil consisted of 0.300-inch by 0.120-inch copper strands insulated with 0.006 inch paper (one side thickness) and 0.003 inch cotton thread, the cotton serving merely as a mechanical protection. This barrier represents the type of major insulation of approximately a 15-kv power transformer.

Barrier *D* consisted of a small coil (more heavily insulated than the one in barrier *C*), a one-fourth inch oil duct adjacent to the coil, two five-sixteenth inch flanged collars, (5) one-eighth inch pressboard sheets, and two one-half inch oil ducts—total thickness two and one-half inch—as shown in figure 4. The turns in the coil consisted of 0.300 inch by 0.100 inch copper strands insulated with 0.138 inch paper (one side thickness) and 0.003 inch cotton thread. This barrier represents the type of major insulation of a power transformer of approximately 92-kv rating.

Figure 5 shows the impulse generator and circuit connections used.

Twenty or more *C* barriers were tested—some on life tests of several hundred shots—before consistent results could be obtained. The difficulty was found to be due to small particles of air entrapped in the coil insulation. The presence of air was very misleading both in the beginning of corona and in the breakdown strength. Quite often, on repeated shots the first appearance of corona gradually disappeared. This process might occur several times as the voltage was increased. During this time the air was eliminated.

As it was not practicable to eliminate the air in the manner usually employed in transformers (by short-circuit heat runs, or evacuation) before starting the tests, it was necessary to assemble the barrier under oil. The coils were dried, oil impregnated, and kept under oil at least 24 hours previous to use and not allowed to come in contact with air during the assembly process. The pressboard, paper sheets, flanged collars, and spacers were all vacuum dried and oil impregnated, and assembled under oil. Approximately 6,000 shots were made on barrier *C* alone after the entrapped air problem was solved. Approximately 4,600 shots were made on barrier *D*. Altogether during the entire investigation some 15,000 to 20,000 impulse tests were made, ranging over a period of approximately two years' time. The investigation proved to be one of the most difficult ones ever followed by the author.

The results of the tests made on barriers *C* and *D* are shown in curve form in figures 6, 7, and 8. The full-wave points are shown at from four to five microseconds' time, regardless of the exact point on the wave at which either corona, injury, or breakdown occurred. The corona no doubt occurred near the crest of the wave (approximately 1.5 microseconds). As has been pointed out, breakdown of insulation barriers also usually occurs near the crest of the wave, though in some cases it may be somewhat beyond the crest—perhaps up to two or three microseconds for a 1.5-microsecond front. Each point represents anywhere from 20 to 100 shots and in some cases several hundred shots were made in graduated steps before corona, injury, or breakdown occurred.

Table II. Impulse Ratios

Negative Full-Wave Impulses	Impulse Ratios for Barriers	
	C	D
1. Single-shot breakdown to one-minute 60-cycle breakdown	$\left(\frac{320}{155}\right) = 2.07$	
2. Repeated shot breakdown to one-minute 60-cycle breakdown	$\left(\frac{280}{155}\right) = 1.8$	$\left(\frac{780}{300}\right) = 2.6$
3. Injurious corona impulse to injurious corona 60 cycle	$\left(\frac{240}{137}\right) = 1.75$	$\left(\frac{680}{275}\right) = 2.48$
4. Injurious corona impulse to one-minute 60-cycle breakdown	$\left(\frac{240}{155}\right) = 1.55$	$\left(\frac{680}{300}\right) = 2.27$

All front-of-wave tests, with one exception, were made by chopping the wave with either 100-centimeter or 200-centimeter spheres. The front of the wave chopped with spheres had no bend-over, as often occurs when chopped with a rod gap. No gap was used when obtaining the single-shot breakdown volt-time curve shown in figure 6, the applied wave being raised on a new barrier after each breakdown. The time and kilovolt values at breakdown were obtained by cathode-ray oscillograms.

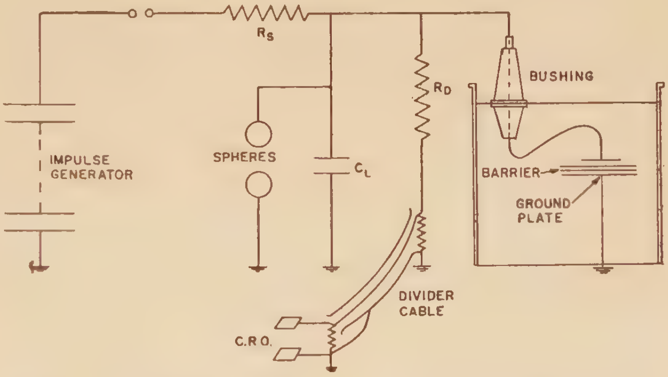


Figure 5. Impulse generator and circuit connections for testing insulation barriers

The curves shown by dashes in figures 6, 7, and 8 and

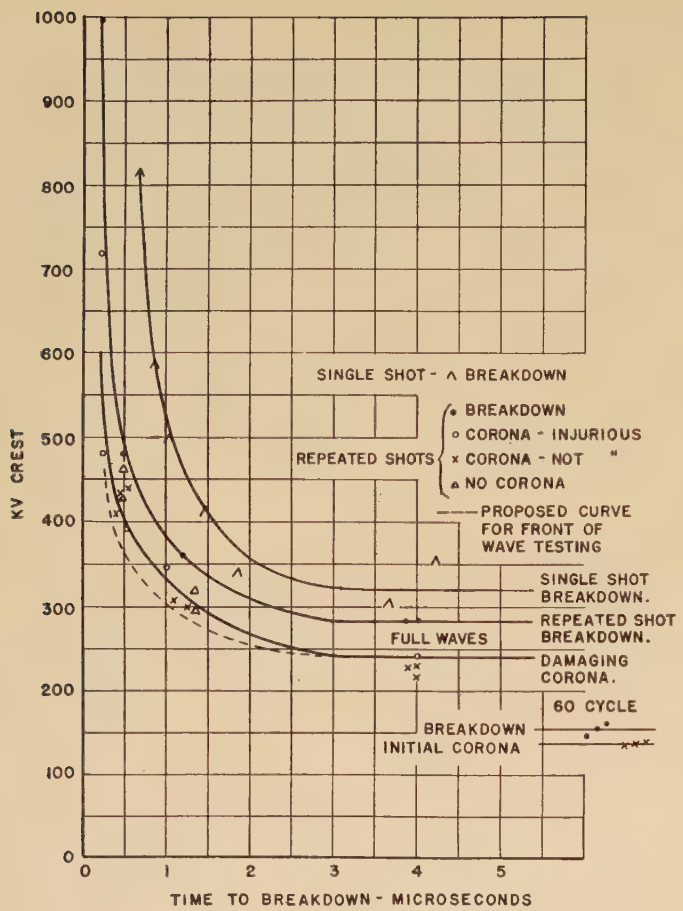


Figure 6. Volt-time curves of transformer insulations; impulse tests on 0.64 inch barrier C; negative waves; 1.5 x 40 used on full-wave tests

marked "Proposed curve for front-of-wave testing" are based on the values given in table I.

Table II gives the impulse ratios obtained on barriers *C* and *D* shown in figures 6 and 7.

The ratio of the injurious corona to the single shot breakdown of barrier *C* was in the order of (240/320) = 0.75.

For positive waves the ratio of the injurious impulse voltage to the 60-cycle one-minute breakdown was (235/155) = 1.52. The full-wave data are rather limited in this case and not much dependence can be placed on them. (Note: The short-time breakdown data are more dependable.)

The results of this investigation indicate that there is no definite impulse ratio that applies to all voltage ratings of transformers.

B. Testing Transformers on Front of Wave

If front-of-wave testing is to be standardized, careful consideration must be given to the rate of voltage rise to be used. Just how steep a wave front should be for front-of-wave testing is an open question. It is not felt that enough is known at the present time of the steepness of wave fronts that occur under service conditions and especially whether or not the same steepness of fronts occur on all rated voltage circuits to make any definite recommendations at this time. The suggestion, however, has been made that a wave whose front rises at the rate of 1,000 kv per microsecond be used for front-of-wave testing of transformers of all voltage ratings. In fact, several high-voltage transformers have recently been tested with this wave by flashing over a rod gap having a spacing in the order of 70 per cent of the (previously standard) test gap.[7]

The present knowledge of direct strokes indicates that the rate of voltage rise is not constant over the whole front of the wave, being lower at the initiation of the wave. Since the same kind of lightning waves will strike both low- and high-voltage circuits, the rate of rise to flashover of the line or station insulation would be less for low-voltage circuits. If 1,000 kv per microsecond is correct for high-voltage circuits it may be only 500 kv per microsecond for low-voltage circuits.

Service records on old transformers protected only by gaps coupled with experience in making factory impulse tests (using 1,000 kv per microsecond wave fronts) on transformers of relatively high-voltage ratings and of similar construction and insulation levels, indicate that seldom are wave fronts as steep as 1,000 kv per microsecond imposed on transformers in service. In other words, based on laboratory tests many of these old transformers would fail if subjected to 1,000 kv per microsecond wave fronts. This absence of failures might be accounted for by the fact that the wave fronts are usually sloped off to less than 1,000 kv per microsecond by attenuation or by the station capacitance—of bus bars, bushings (for both circuit breakers and transformers) and of the

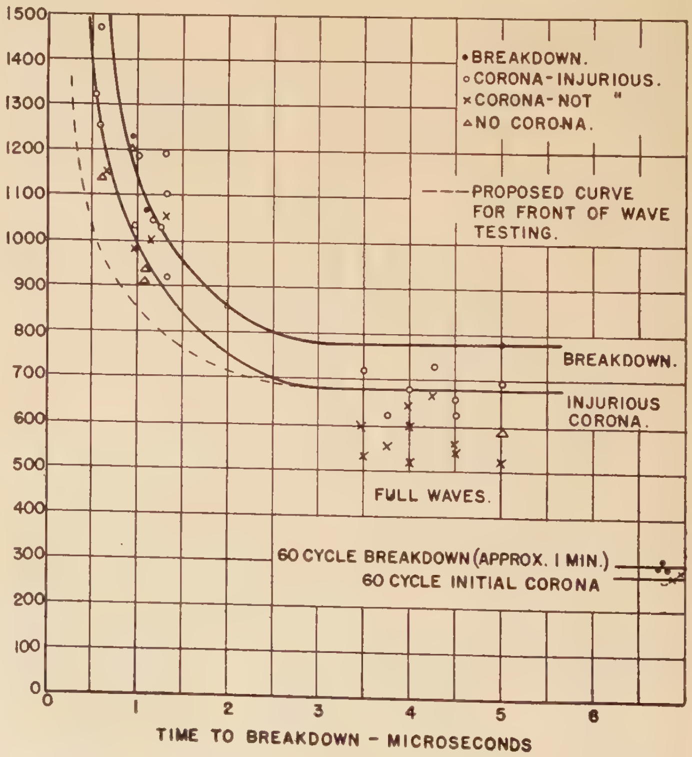


Figure 7. Volt-time curves of transformer insulations; impulse life tests on 2.5 inch barrier D; negative waves; 1.5x40 used on full-wave tests

transformer windings. This indicates that 1,000 kv per microsecond rate of voltage rise might be too high for front-of-wave testing, especially for transformers of the lower voltage ratings.

Front-of-wave testing can be specified in either of two ways; first, by kilovolts and time; second, by inches of rod gap and rate of voltage rise. In either case the kilovolts imposed on transformers in front-of-wave testing should be governed by the volt-time curve of transformer windings if the same factor of safety is to be maintained for full waves, chopped waves, and front of waves. Until the EEI-NEMA subcommittee on correlation of laboratory data establishes volt-time curves for gaps, insulators, etc., it appears that some front-of-wave tests will be specified by gap spacings. The preferable method, however, is to specify the tests by kilovolts and time to flashover of a gap.

Specifying front-of-wave testing by inches of rod gaps is more involved than specifying the test by kilovolt values for the reason that the proper gap spacing depends upon the way the rate of rise is defined. There are two ways of defining the rate of rise; namely,

First, the rate of rise is determined by the slope of a straight line drawn through the 10 and 90 per cent voltage points. This is usually termed the "effective" rate of rise.

Second, the rate of rise corresponds to the slope of a straight line drawn from virtual zero to the time of actual flashover. This is termed the "average" rate of rise.

NOTE: In either case "time" starts from "virtual time zero" which is determined by drawing a straight line through the 10 and 90 per cent voltage points. The intersection of this line with the time axis (zero voltage line) is the virtual time zero.

If there is no bend-over just before flashover, both the effective and average rates of rise are, of course, the same.

However, when using a rod gap to chop the wave front, there may be an appreciable bend-over just before flashover takes place (due to heavy corona current drawn by rod gap), in which case the effective rate of rise will be greater than the average rate of rise. This is illustrated in figure 9. Merely applying a higher voltage will not entirely eliminate the bend-over.

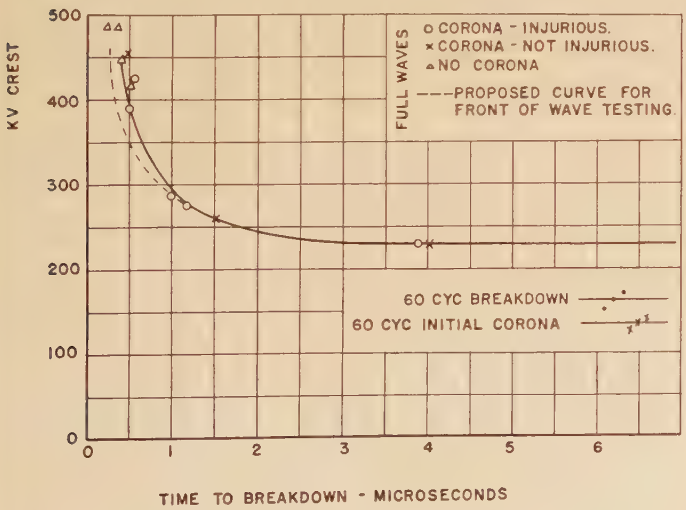


Figure 8. Volt-time curves of transformer insulations; impulse life tests on 0.64 inch barrier C; positive waves; 1.5x40 for full-wave tests

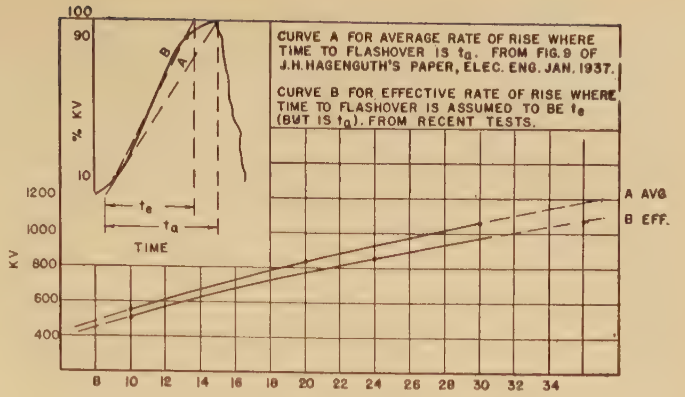


Figure 9. Impulse flashover of rod gaps, 1,000 kilovolts per microsecond; negative wave fronts

The remainder of the discussion of this subject will be based, merely for illustrative purposes, upon testing transformers with a 1,000 kilovolts per microsecond wave front. It should be understood, however, that this does not mean that a 1,000 kilovolts per microsecond wave is advocated for front-of-wave testing for the reasons previously mentioned. If some other rate is used where the test is specified by gaps, the same method should be used to determine the proper gap spacing.

The impulse flashover of rod gaps at 1,000 kilovolts per microsecond wave front is shown in figure 9, where curve *A* is based on the average front and curve *B* on the effective front.

Curve *A* is based on three points for 10-, 20-, and 30-inch gap spacings taken from figure 9 of reference 8. Curve *B* is based on two points for 10-inch and 24-inch rod gaps recently taken in the Pittsfield works high-voltage laboratory.

As previously pointed out the proper kilovolts to use for front-of-wave testing of transformers with standard insulation should be based on the volt-time curve of transformer insulation. Figure 10 shows the volt-time curves of transformer insulation based on (1) breakdown by single application of voltage, curve *A*, and (2) breakdown by repeated applications of voltage, curve *B*.

We are now in a position to select the proper kilovolt values and proper gap spacings (when the test levels are specified by gaps) for impulse testing power transformers having standard insulation levels and where the specified wave front is 1,000 kilovolts per microsecond and of negative polarity.

If the time of gap flashover is 0.6-microsecond (determined by cut-and-try method) the impulse kilovolts by curve *A*, figure 10, should be 1.44 times the long (chopped) wave (chopped) test kilovolts.

Table II of article "Insulation Strength of Transformers"[9] gives the chopped wave test as 405 kv for a transformer of 69-kv rating.

Therefore, the front-of-wave test voltage for a 69-kv transformer should be 405 × 1.44 = 583 kv which flashes over in 0.583 microsecond (or approximately 0.6 microsecond) at 1,000 kilovolts per microsecond. If the tests were specified by rod-gap spacing, the lengths of gap (by curves in figure 9) for 583 kilovolts should be approximately 11 inches (by curve *A*) for an average wave front of 1,000 kilovolts per microsecond and approximately 13 inches (by curve *B*) for an effective wave front of 1,000 kilovolts per microsecond.

It should be kept in mind that if the average rate of rise (line *A*, figure 9) is 1,000 kilovolts per microsecond, the effective rate of rise will be more than 1,000 kilovolts per microsecond—in the order of 1,200 to 1,500 kilovolts per microsecond, depending on the bend-over of the wave. It is for this reason that the gap spacing should be less when using average rate of rise.

In a similar manner the test-gap spacings were determined for 92-, 115-, and 138-kv transformers having standard insulation levels. The results are given in table III.

The above shows that the test-gap spacing for front-of-wave testing will depend not only upon the insulation level but also upon the method of defining the rate of voltage rise. It should be kept in mind that while the gap spacings are different in the last two columns, they represent the same flashover kv values. Further laboratory data are needed on 1,000 kilovolts per microsecond flashover of rod gaps below ten inch and above 30 inch spacings before working out gap spacings for other circuit kilovolt ratings, especially ratings above 138 kv.

Furthermore, as the curves in figure 9 are based on limited data from only one laboratory, the spacings shown in table III are subject to change when final volt-time curves for rod gaps are agreed upon by the EEI-NEMA subcommittee on correlation of laboratory data. The main purpose in presenting this data is to show the proper method of deriving gap spacings for front-of-wave testing.

Table III. Rod Gap Spacings for Front-of-Wave Tests of Power Transformers

Rated Circuit Kv	AIEE Recom. Chopped Wave Kv	Multiplying Factor	Front-of-Negative-Wave Tests			
			Kv	Approx. Time to F. O. μ sec	Gap Spacing—Inches for 1,000 Kv per μ sec	
					Eff. Front	Avg. Front
69	405	× 1.44	= 583	0.6	13″	11″
92	515	× 1.38	= 710	0.7	18	15.5
115	625	× 1.33	= 830	0.83	23.5	20
138	750	× 1.27	= 950	0.95	30.0	25.5

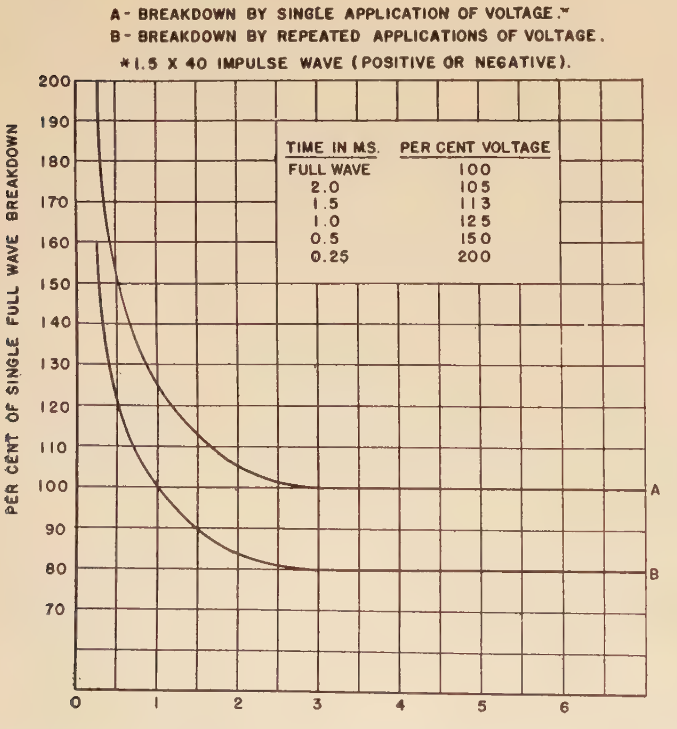


Figure 10. Volt-time curves of insulation, consisting of solid insulation and oil in series (simulating major insulation in a power transformer)

Protecting Old Power Transformers Against Steep-Front Waves by Rod Gaps

It should be realized that the bend-up of volt-time curves of insulation shown in figure 10 does not necessarily apply to old unshielded transformers where the impulse stresses between turns and between coils are much higher for steep-front waves than for long waves of the same applied kilovolts. This is true mostly for the higher-voltage ratings where the windings were not shielded to prevent excessive voltage stresses between turns and coils when subjected to steep waves.

In other words, while figure 10 shows the shape of volt-time curves for the major insulation for both old and new transformers it does not necessarily represent the shape of the volt-time curve for turn to turn and coil to coil insulation for all transformers in service. In some cases of old transformers it may not be possible to permit any turn-up in the volt-time curve. It should be understood, however, that this reduced turn-up is not due in any way to the characteristics of the insulation itself but rather to the increased turn and coil voltage stresses (as expressed by percentage of the applied wave) resulting from steep waves. In all cases the flat part of the curve, figure 10, should correspond to the safe long wave (1.5 × 40) impulse test level of the transformer.

Conclusions

The following conclusions have been drawn from this investigation, taking into account the tests made on the barriers, *A* and *B*, with bare line electrodes as well as barriers *C* and *D* with insulated line electrodes.

1. The breakdown of insulation by repeated impulse voltage is not associated with any heating effect. That is, the breakdown is independent of the duration of the wait between shots.
2. The volt-time curve of transformer insulations based on repeated voltage applications is essentially of the same shape as (although of lower value than) the volt-time curve based on single voltage applications.
3. There is no polarity effect on either the beginning of corona or the breakdown of insulation. (Note: If any polarity effect exists for insulation it should have shown up in these tests made with a small coil as one electrode and a plane 36 inches by 46 inches as the other electrode.)

4. Streamer corona damages insulation, while glow or brush discharge corona under conditions within the limits of this investigation (impulse of short time duration compared to 60 cycles) may not cause any measurable damage. There is no definite voltage at which corona of the brush discharge type first occurs on a given barrier.

5. The corona band on the edges (either inside or outside) of the coils with turn insulation was generally wider on full waves than on steep-front waves. In some cases on life tests there was no visible corona on the coil with steep waves until puncture occurred. The kv at which corona appeared on different coils, however, varied to some extent for steep waves.

6. With bare line (generator-side) electrodes the ratio between the repeated shot injurious corona and the repeated shot breakdown (reached by graduated voltage steps of 100 shots at each step) varies over quite a range. In some cases the repeated shot injurious corona was as low as 65 per cent of the single shot breakdown while the breakdown with 100 or more shots was as high as 90 per cent of the single-shot breakdown.

7. With an insulated line electrode the injurious corona on full waves generally ranges from approximately 75 per cent to 85 per cent of the single shot breakdown although in some few cases it was as high as 90 per cent. While the repeated-shot strength (100 shots or more) may be higher than the injurious corona point, the volt-time curves of repeated shot strengths of insulation should be based on the injurious corona level since failure would eventually take place if enough shots were applied. A safe over-all average value to use appears to be about 80 per cent.

8. When front-of-wave testing of transformers is desired it is preferable that the test be specified by kilovolts and time—the values being based on the volt-time curve of transformer insulation, figure 10. If the larger gap spacings (last two columns of Table III) are specified the effective rate of rise should be used.

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Discussion

J. E. Clem (General Electric Company, Schenectady, N. Y.): Mr. Montsinger has given us another paper which should be useful in improving the design of transformers in regard to their lightning-strength characteristics. This discussion will suggest an application of the material in the paper.

It is interesting to note that the data in table I can be closely approximated by a simple empirical expression as follows:

$$R = 0.75 \times \frac{0.5}{t^{\frac{2}{3}}}$$

Table I. Impulse Volt-Time Values by Test and Equation

Time t to Breakdown (Microseconds)	Ratio R of Breakdown Voltage at Time t to Full-Wave Breakdown Voltage	
	Paper	Equation
0.25	2.00	2.010
0.5	1.50	1.544
1.0	1.25	1.250
1.5	1.13	1.132
2.0	1.05	1.065
3.0	1.00	0.990

R = ratio of voltage at breakdown to full-wave breakdown voltage.

t = time to breakdown in microseconds.

See table I of this discussion for comparison of test and calculated values.

The average steepness to the point of cut-off of the wave front of lightning as it appears on transmission lines is less for the lower-voltage circuits than for the higher-voltage circuits. Measured values of kilovolts per microsecond range from 40 to 2,000 with only a few exceeding 500 volts per microsecond. These facts should be considered in any proposals for wave-front testing of transformers.

When the present Institute Impulse Test Code was first prepared it was recognized that changes or additions probably would be necessary, as the knowledge of the nature of lightning increased and as experience in testing developed. The basic reason for setting up impulse tests is to establish definite insulation values which may be demonstrated by test and which may serve as a measure of the protection which must be provided when the transformer is in service.

It has long been recognized that the main source of damaging overvoltages is lightning and accordingly the impulse test should be of such a nature that the results can be correlated with operating conditions. The present impulse test consists of two applications of a chopped wave followed by one application of a full wave. This test simulates to a certain degree traveling waves and waves chopped some distance from the station. However, the Institute should consider some test which better demonstrates the insulation level of transformers for conditions corresponding to a nearby direct stroke which imposes a very rapidly rising voltage.

There has been a demand for tests of this latter nature, in which a wave of a specified rate of rise and magnitude is applied to the transformer. In order that there be a common basis for specifying the test requirements and making the tests I am proposing that the Institute immediately begin the preparation of standards for front-of-wave testing of transformers.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): Mr. Montsinger has presented a paper setting forth the results of

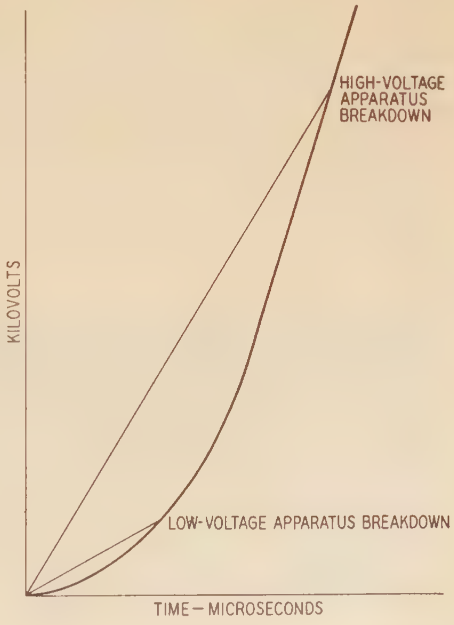

Figure 1. Effect of wave shape on rate of rise from zero volts

an investigation in the high-voltage engineering laboratory on transformer insulation under front-of-the-wave conditions. It must not be inferred, however, that information is available as yet indicating how steep the waves may be expected to be in practice. A figure of 1,000 kilovolts per microsecond has been mentioned and used at times, but it is not known how often such a wave front would be measured in service. Most of the data on wave front comes from the work of Norinder,[1] but these results must be used with caution on account of the possibility of error.

Furthermore, although the author is discussing only power-transformer insulation, yet I think it is wise to point out that rates of rise, to be expected for low-voltage circuits, may well be appreciably less than for high-voltage equipment. This situation is illustrated in figure 1, which shows the probable shape of a direct stroke of lightning initiated by a downward leader. McEachron[2] and McMorris have shown that this wave shape would be expected as the result of the motion of propagation of the downward leader carrying a charge. The only oscillogram[3] measuring the potential of a direct stroke of lightning close by also indicates the same kind of front. I have no doubt but that many kinds of fronts are possible, but figure 1 indicates that the same rate of rise should not be applied to low-voltage transformers as is applied to the high-voltage transformer, on account of the lower insulation level.

Attention is being directed toward the securing of wave-shape data, but it cannot be obtained quickly, even after means and methods are devised for making a sufficient number of measurements to be significant. This all states that much care must be taken in undertaking any program of front-of-wave testing, and low-voltage transformers will require in all probability lower rates of voltage rise than high voltage transformers.

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P. L. Bellaschi (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Montsinger has presented a valuable contribution on the co-ordination of transformer insulation to steep-front impulse waves. Similar extensive investigations at the Sharon high-voltage laboratory have established that what has been accomplished for the distribution transformer in the way of self-protection against lightning strokes[1] appears feasible and economical also for the modern power transformer.

One of the factors which has contributed to this development is the ability to produce and measure in the laboratory steep-front impulse waves. For example, typical rod-gap values obtained at Sharon for the 15-inch and 24-inch spacings for a 1,000 kv per microsecond effective rise are respectively, 620 kv and 830 kv. The good agreement of the corresponding Pittsfield data in figure 9 suggests that some standardization is quite possible at this date. In so doing naturally a closer comparison of technique and test methods may become necessary.

An important consideration in comparing results is the ratio of the average to the effective front as this ratio is a measure of the shape of the wave and of the rounding at the chopped crest. The experience at Sharon in testing many barriers and a number of transformers has shown that this ratio for the various conditions hereto encountered has ranged from 0.70 to practically 1.00. On the average the ratio is in the order of 0.85 which indicates that the wave in general is quite sharp at the crest. Locating the rod gap right at the bushing of the apparatus tested and operating the impulse generator as high up in the voltage setting as possible with respect to the chopped test voltage should contribute to a front in which the ratio of average to effective is high, such as the oscillograms of the transformer model tests given in figures 2 and 3 show.

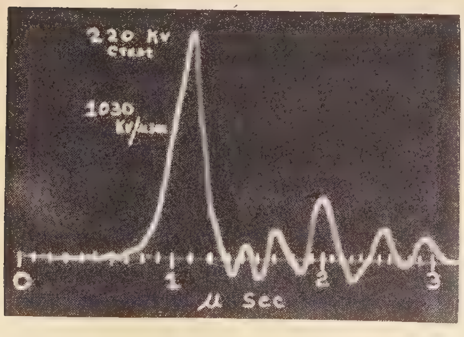

Figure 2. Commercial impulse test on 13.8-kv transformer. This oscillogram also illustrates the impulse voltage applied repeatedly to a 13.8-kv transformer model

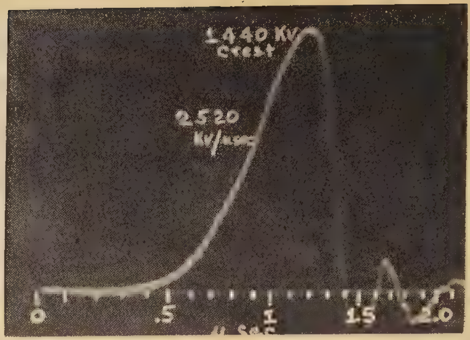

Figure 3. Impulse voltage applied to 138-kv transformer model

The conclusion Mr. Montsinger arrives at in table III where quite different rod gap values are set up for each of the two methods of defining the front, is difficult to understand. The insulation characteristic in figure 10 is a volt-time curve, therefore the rod-gap schedule under the average front column appears as the logical one. The appreciable difference in the gap values for the average and the effective front columns is hardly to be expected for the reason that the insulation characteristic and the rod gap characteristic each vary in the same direction and about the same relative amount. For example, increasing or decreasing the basis of the rate of rise in table III either to 1,500 kv per microsecond or 750 kv per microsecond (according to the Sharon rod-gap data) would indicate substantially the same schedule of rod gaps. In other words by virtue of the close similarity in the insulation and rod-gap characteristics over a certain range of the time once the correct schedule of gaps has been established co-ordination for the shorter or longer impulses should be expected. It is clear, too, on this score that the method of testing would be rather immaterial. On the other hand there are certain advantages inherent in the effective method, as better control in testing. The effective front responds more directly to generator setting and is accordingly subject to somewhat better control.

Mr. Montsinger indicates that reason for a 1,000 kv per microsecond rate of rise as a basis for testing transformers. From the extensive experience of apparatus in the field that has given adequate service and judging the relative ability of this old apparatus in withstanding the steep-impulse tests that have been applied to modern transformers, the 1,000 kv per microsecond appears in general quite justified. The measurements taken at the end of the 220 kv Wallenpaupack-Siegfried line several years ago[2] indicated front steepnesses lower than 1,000 kv per microsecond. On the other hand an oscillograph record[3] measured within a few hundred feet of a stroke to this same line shows a rate of rise in the order of 1,500 to 2,000 kv per microsecond. Had there been a substation close by, the front at the apparatus quite likely would have suffered some reduction due to the station capacitance. There have been indications of steeper fronts appearing on wood-pole lines with no ground wire as the result of direct strokes to the line conductors and the high insulation level of the line. A rate of rise apparently as high as 5,000 kv per microsecond seems to have been measured.[4]

While abroad this past summer, the writer had the occasion to discuss with various investigators the problem of the probable rate of rise of lightning. One of the more important field studies in this connection has been the investigation in Switzerland under the direction of Doctor K. Berger.[5] Oscillograph records taken at one important substation which connects to a 150-kv line and where an 80-kv line terminates, have not to this day indicated fronts up to 1,000 kv per microsecond, though direct strokes on the lines have rather frequently occurred. In an interesting analysis prepared for

IEC,[6] Doctor Berger calls attention to the possibility of impulse voltages attaining a rate of rise as high as 5,000 kv per microsecond—figure representing the upper limit, such as in the case of a severe direct stroke to the line conductor. These impulses attenuate rapidly and as stated above the station capacitance would contribute also in reducing the steepness. For lines properly shielded with ground wires and having reasonably low tower-footing resistance, even in the case of a back flash onto the line a rate of rise steeper than 1,000 kv per microsecond does not appear probable.[6] With due weight to the investigations and experiences on lightning-stroke phenomena both here and abroad, in my opinion the 1,000 kv per microsecond rate of rise for testing transformers is as sound a figure as our present knowledge will permit.

The tests on distribution and power transformers with steep impulses such as shown in figures 2 and 3 mark quite a step in the progress of insulation co-ordination. In view of the greater difficulty steep-front impulse testing should however, be considered more in the nature of a type test. Somewhat greater tolerance should, for the present at least, be recognized in making such tests as compared to the standard AIEE tests on full wave and waves chopped on the tail.[7]

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L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): Mr. Montsinger's paper is worthy of considerable interest. When it is realized that the data in his paper represent approximately 10,600 impulse tests, the difficulty of obtaining reliable data relating to impulse phenomena may be better appreciated.

After considering the data submitted by Mr. Montsinger, a few questions arise. These refer to figures 6, 7, and 8 in the advance copy of the paper. It will be noted the ordinates of the curves are labeled "kv crest." From this, one assumes the 60-cycle values are also in crest kilovolts.

Consider, first, figure 6, which represents an insulating barrier for a 15-kv class transformer. The AIEE low-frequency dielectric test for this class is 34 kv effective, or 48 kv crest. Assuming the plotted 60-cycle corona and breakdown values as crest kilovolts, it is found the factor of safety or ratio of 60-cycle initial corona to low frequency dielectric test is 137/48 = 2.85. This appears to be a reasonable factor of safety.

Upon going to figure 7 and the 92-kv class of insulating barrier, a different picture develops. For this class the low frequency dielectric test is 185 kv effective, equivalent to 261.2 kv crest. Mr. Montsinger's data give the 60-cycle initial corona point as 275 kv, which gives a factor of safety of 275/261.2 = 1.05, a value which seems too close for 100 per cent assurance against damaging the insulation even before the transformer has left the manufacturer's shops.

Because of the wide spread between impulse injurious corona and one-shot breakdown, it is of course essential to design transformers using the injurious corona as the impulse strength of the transformer. If encroachment is made into the region above the injurious corona level, damage may be done without knowing it. As the transformer must withstand the crest value of the chopped wave when subjected to an impulse test, it is essential to regard this figure rather than the lower full-wave impulse shot as the one determining the impulse ratio.

Referring to figure 6, the impulse injurious corona level is found to be 240 kv. In accordance with the latest recommendations of the transformer subcommittee, the chopped-wave crest for this class is 130 kv, resulting in a factor of safety of 240/130 = 1.85. For the 92-kv class the impulse injurious corona level is 680 kv, and the chopped-wave crest value is 515 kv, giving a factor of safety of 680/515 = 1.32.

No mention is made of the method used to determine the point of initial corona under impulse test. Injurious corona can be detected by markings, but initial corona supposedly is non-injurious to the material and would leave no mark; hence an outline of the method used would be of interest.

J. H. Hagenguth (General Electric Company, Pittsfield, Mass.): Mr. Montsinger clearly points out the necessity of differentiation between an impulse test made with a 1.5 x 40 wave and a wave having a rate of rise of say, 1,000 kv per microsecond. Whether or not steep-front tests are desirable and what rate of rise should be used for transformers of different voltage classes has to be decided on consideration of actual lightning fronts (information of which is meager) and on tests such as described in the paper. If practical, these tests should be supplemented by steep-front tests to establish volt-time curves for turn, coil, and major insulation.

Several front-of-wave tests have been made on a commercial basis by the laboratory with which I am connected. The results of these tests were satisfactory from the point of view that failure did not occur. The kilovolt ratings of the windings tested, and the impulse voltages applied are given in table I of this discussion. At present, no method of definitely detecting small failures, such as turn-to-turn failure or coil-to-coil failure is available. My experience has shown that normal-frequency voltage applied to experimental transformers has never resulted in follow currents although failure due to impulse was detected by other methods. This type of failure, however, is progressive and finally will cause a normal frequency short circuit, when the failure path is sufficiently carbonized. In transformers with uniform voltage distribution the front-of-wave test limits of figure 10 of the paper apply probably for the transformer as a unit

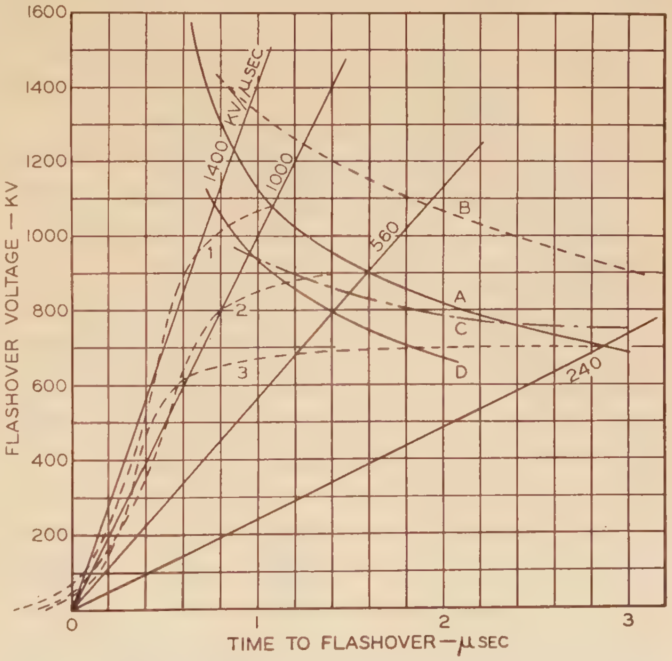


Figure 4. Flashover voltages of a 30-inch rod gap on the front of the wave, negative polarity, for 1,000 kv per microsecond rate of rise

Wave 1—On the basis of average rate of rise

Waves 2 and 3—On the basis of effective rate of rise

Curve *A*—Volt-time curve for 30-inch rod gap obtained with 1.5 × 40 wave

Curve *B*—Volt-time curve for 30-inch rod gap obtained with practically straight-line voltage rise, flashover on the rising front

Curve *C*—Volt-time curve of transformer insulation, 138-kv voltage class

Curve *D*—Volt-time curve of 25.5-inch rod gap obtained with 1.5 × 40 wave

Straight lines indicate rate of voltage rise in kilovolts per microsecond since turn insulation exhibits characteristics similar to the sample barriers tested. Transformers with poor initial voltage distribution would be subjected to considerably higher internal stresses during the steep front test than during the present standard AIEE. A point of some concern is the method of testing with steep-fronted waves.

1. VOLTAGE MEASUREMENT

At short times to flashover the flashover voltage measured by different laboratories for a given spacing and time to flashover differs by 20 per cent and more. This is mostly due to the use of different types of voltage dividers. It appears, therefore, doubtful, that a test standard could be devised on the basis of flashover voltage of a rod gap, at present, because this would definitely mean that transformers of different manufacturers were receiving tests of different severity. Similarly, of course, it seems quite impossible to use the rate of rise of the wave as a standard measure, since this in turn would imply a more exact knowledge of the actual flashover voltage.

2. ROD-GAP METHOD (TEMPORARY EXPEDIENT)

For the reasons stated above, rate of rise does not appear as a satisfactory yardstick for impulse testing at present. However, rod-gap spacings can be specified for the various voltage classes of transformers which have been found by experience to be capable of limiting the applied voltage to a maximum voltage value. The spacing alone would not suffice to assure application of similar voltage waves to a transformer by different manufacturers (as will be shown later) and it is necessary to specify the maximum time to flashover to be measured by a cathode-ray oscillograph. Irrespective of the type of divider used, the time to flashover will be measured with almost equal accuracy and a test specification of this type should, therefore, yield uniform test results by all manufacturers. The principal objection against the use of rod gaps in the present standard was that its flashover voltage varies greatly with humidity. The humidity effect is less objectionable for front-of-wave tests since at short times to flashover the humidity correction is greatly reduced. For instance, at 0.5 microsecond, the correction seems to be zero, at 2 microseconds it is only a fraction of the correction for the 1.5 x 40 wave.

This type of testing, of course, is very crude and reminds one of the early beginning of impulse testing, where rod gaps were used for similar reasons. It, therefore, should be considered only as a transitory measure to be replaced by volt-time measurements as soon as standardized voltage measurements and short-time flashover values of gaps and insulators are agreed upon by the EEI-NEMA laboratory group.

At that time sphere-gap spacings should perhaps be used rather than rod gaps, although this would mean the use of two different types of gaps during a complete impulse test. For waves of the present standard test requiring a chopped wave with flashover occurring at a specified minimum time the sphere gap would be unsuitable, at least for voltage classes of 25 kv and up. Considerably more information will be required of short-time flashover voltages of small spheres and the use of ultraviolet light to diminish the time lag and erratic arcing.

I would like to emphasize at this time, however, that it appears advisable even now to definitely standardize on one definition of voltage rise, and that is average rate of rise, whether sphere gaps or rod gaps are used for chopping the wave. At present, two are in use as defined in the paper: average rate of rise and effective rate of rise. The use of the latter term leads to confusion and lacks precision as will be explained by the use of figure 4 of the discussion. For illustrative purposes this figure has been drawn for a 30-inch rod gap. Curve *A* represents the volt-time curve of a 30-inch rod (as recommended for front-of-wave testing for 138 kv rated circuit voltage) obtained with a 1.5 x 40 wave. Curve *B* represents the volt-time curve of a 30-inch rod gap obtained with waves rising at substantially a uniform rate of rise. Curve *C* represents the safe voltage limits for power transformers of the 138-kv voltage class. Curves *A*, *B*, and *C* were obtained using the same methods of measurement and are, therefore, directly comparable. Superimposed on these curves are straight lines representing different rates of rise. The question of average and effective rate of rise would be irrelevant if the wave fronts applied to the test piece were straight lines, because then the voltage and time to flashover would be the same using either definition. However, waves usually obtained are of the form shown by curves 1, 2, and 3. Curves 2 and 3 represent waves, both of which have an effective rate of rise of 1,000 kv per microsecond. The straight line represents another front at 1,000 kv per microsecond and, therefore, the following values of flashover voltage and time to flashover could be obtained for waves of the same rate of rise on the front.

Table II

Wave	Flashover Voltage	Time	Per Cent Kilovolts
1	1,070	1.07	100
2	900	1.6	84
3	700	2.87	65.0

This table, I believe, shows clearly that the effective rate of rise is too loose a term and cannot be used as a standard of measurement, especially since it can lead to a condition where steep-front waves of the required rate of rise are applied, but the amplitude is decreased by making the time to flashover long. For instance, the flashover voltage of curve 3 of figure 4 (this discussion) would actually be lower than the specified chopped wave voltage of the present standard test with 1.5x40 wave.

On the other hand, the use of average rate of rise establishes definite limits. For instance, curve 1, figure 4 (this discussion) represents a typical wave which would be applied during a test specified by average rate of rise of 1,000 kv per microsecond. The flashover voltage with this definition cannot be made to be materially lower than, 1,070 kv but rather can be increased by straightening out the wave front to reach a possible maximum of 1,240 kv. In this case, therefore, the bend over of wave front is entirely beneficial to the transformer as far as the amplitude of the voltage is concerned and yet the flashover voltage cannot be lowered materially without obtaining too low a rate of rise, i.e., if the kilovolt value were reduced to 1,000 kv (flashover at 1.26 microseconds) the rate of rise would be reduced to 800 kv per microsecond which would be too low to conform with specifications.

A further advantage of the use of average rate of rise is that it can be obtained from any volt-time curve by simply dividing the flashover voltage by the time to flashover, while the use of effective rate of rise requires entirely separate curves which will be a function of the bend over of the curve as illustrated by curves 2 and 3, figure 4 (this discussion). For instance, curve *B* of figure 9 of the paper applies only to one particular wave front used. Any number of such curves could be drawn, the highest one would coincide with curve *A* while curves with flashover voltages lower than *B* would be entirely possible.

It appears, therefore, necessary that in the final standard for front-of-wave testing, crest voltage and time to flashover or crest voltage and average rate of rise be specified and that the use of effective rate of rise be discontinued.

Concerning the rod-gap spacings to be used at present for front-of-wave tests, figure 4 (this discussion) shows that if average rate of rise is used a rod gap spacing of 25.5 inches (curve *D*, figure 4, this discussion) is required to limit the flashover voltage to 950 kv. This checks values given in table III of the paper. If a rod-gap spacing of 30 inches is used as shown in the paper for effective rate of rise, the flashover voltage should be limited to about 755 kv in order not to exceed the safe limits of the transformer. The time to flashover in this case would be approximately 2.4 microseconds. This test, therefore, would, practically speaking, be exactly the same as the chopped-wave test of the present Impulse Test Standards. Therefore, if the gap spacing of 30 inches is used, either the safe insulation limits are exceeded by up to 25 per cent or if the voltage is kept below the safe limits of the transformer, the value of the test is doubtful, since the only difference from the present chopped wave is the steeper front.

F. J. Vogel (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Montsinger has made a real contribution in furnishing data on the strength of insulation under oil. Such tests as those described are indeed difficult and expensive to make. By increasing our knowledge of the behavior of materials, we are provided on the one hand with information necessary to determine what is possible, and on the other hand how to accomplish these possibilities with reasonable factors of safety in actual designs.

When data are furnished, it is usually possible to draw many diverse conclusions from it. It is often dangerous to draw conclusions from another's data but nevertheless there are certain interpretations of Mr. Montsinger's tests which are of great interest and it seems to me that they should be noted.

Barrier *C* is indeed an approximation of 15-kv transformer major insulation, except for the extension of the barrier beyond the coil. It is my impression that in actual transformers, the extension is of the order of one or two inches for the 15-kv class; it is believed that this extension is not generally sufficient to result in puncture, but that the insulation would fail by creeping around the barrier. In Mr. Montsinger's paper this extension was 13 or 14 inches, sufficient to result in a puncture of the barrier *C* in the tests. However, taking the full-wave value of 240 kv as correct for 15-kv insulation, it is possible to show certain relationships. My figure 5 shows time-voltage values for the five and three-fourths inch gap as determined in Sharon, compared directly with Mr. Montsinger's curve figure 6. There is a margin of 30 per cent between these curves, even at extremely short times. This curve indicates to the writer that it might be possible economically to make transformers of this type of construction completely co-ordinated. Barrier *C* is typical, depending upon the manufacture, of transformers insulations up to 46 kv, except for the amount of extension. The barrier thickness will, of course, vary up to one or one and one-half inches or more.

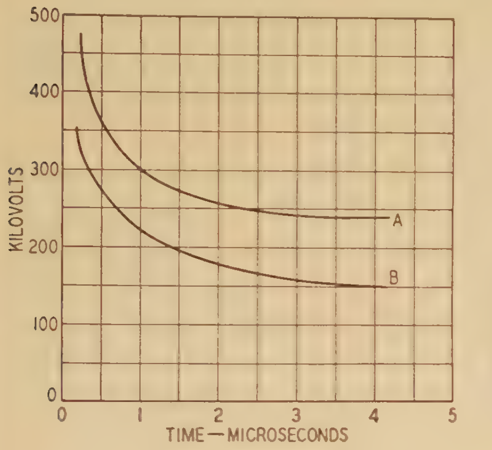


Figure 5

A—Data for barrier *C*, 13.8-kv insulation, Mr. Montsinger's paper "Co-ordination of Power Transformers for Steep-Front Impulse Waves," figure 6

B—Data for five-and-three-quarters-inch rod gap, negative waves

Barrier *D* is described as typical of approximately 92-kv class insulation, tested at 185 kv root-mean-square. It is to be noted that 275 kv crest is 194 kv root-mean-square; 275 kv crest at 60 cycles is the maximum voltage which barrier *D* will withstand without injurious corona. If the insulation in an actual transformer, is not to be injured on test at 185 kv root-mean-square, there must be a margin in the design. According to table II, row 3, the insulation would withstand without corona, full waves of 680 times 185 divided by 194 or 650 kv, with the designer's margin. One might reduce this value somewhat further by taking the lowest value for injurious corona instead of the average value which would reduce the figure to 590 kv. The data on figure 7 may then be redrawn as shown in figure 6 to be representative of 92-kv class insulation. For comparison, a curve given by Mr. Hagenguth for a 20-inch gap, published in the January issue of Electrical Engineering, is also shown. This would indicate that a 20-inch gap could protect a 92-kv transformer against extremely high voltages for extremely short times, even for direct strokes of lightning. It is to be noted that barrier *D* is similar to the insulation generally used in the 69-kv class and above and similar relationships should hold. This would tend to confirm Mr. Montsinger's opinion that it is impractical to build completely co-ordinated transformers when a gap alone is to be relied upon.

The results of tests on barrier *D* only confirm my opinion further that higher impulse strengths should be obtained than those at present standardized for the higher voltage classes. Data published by the writer has been chiefly on the basis of interleaved insulation similar to barrier *D* and typical of actual transformer insulation. Mr. Montsinger's data also show 2.2 to be a fairly average value for the ratio between impulse and 60-cycle breakdown and corona voltages for interleaved insulation. Under these circumstances, it is difficult to see why a 570 kv is not a more reasonable value for impulse-testing 92 kv insulation than the present AIEE subcommittee recommendations of 515 kv. This is particularly true when the higher value is desirable from the standpoint of obtaining protection under the worst conditions. Whether Mr. Montsinger is correct or not in stating that there is no definite impulse ratio that applies to all voltage ratings of transformers, he has at least furnished confirming evidence that ratios of 2.2 or higher can be obtained with some constructions. Further it would seem that the impulse strength is really the important one from the service standpoint and that the 60-cycle test is relatively unimportant. If present impulse test values are retained, it would seem that the 60-cycle test values might be abandoned or at least reduced in order to provide a greater degree of flexibility for the designer.

It is difficult to see how it is possible to change the gap values as much as Mr. Montsinger states when using effective values as compared with average values. Referring to figure 7 in my discussion, a sample oscillogram is shown and the two methods of interpretation described by Mr. Montsinger are illustrated. These data can be plotted on the curve using either average or effective times. This curve shows how a higher voltage will be obtained for a given rate of voltage rise using the average value. Assuming that these curves apply for a rod gap, is there any reason to believe that similar curves do not apply to transformer insulation? If so, figure 8 shows what might be obtained for transformer insulation. Mr. Montsinger, in his method of deriving gap lengths, is really comparing volt-time curves for gaps with similar curves for transformer insulation. If average values are used to compare results, it is seen that we obtain approximately the same length as obtained by Mr. Montsinger. If we compare the effective values for the rod gap with the average rate-of-rise data for the insulation, we find that the gap can apparently be increased. The writer does not believe this to be actually the case. It is suggested that to prove this, it might be desirable to test insulation, protected by a rod gap, with different shapes of waves to see if there is really a difference, as Mr. Montsinger believes. It would be desirable for another reason also. Those customers desiring tests with gaps and steep-wave

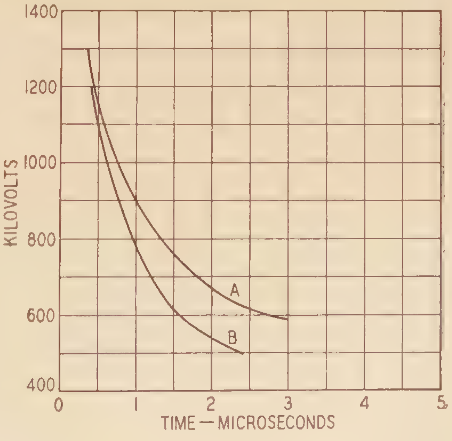


Figure 6

A—Data for barrier reduced to 92-kv class, Mr. Montsinger's paper "Co-ordination of Power Transformers for Steep-Front Impulse Waves," figure 7

B—Data from maximum values for 20-inch rod gap (positive or negative), Mr. J. H. Hagenguth's paper "Short-Time Spark-over of Gaps," figure 14, ELECTRICAL ENGINEERING January 193

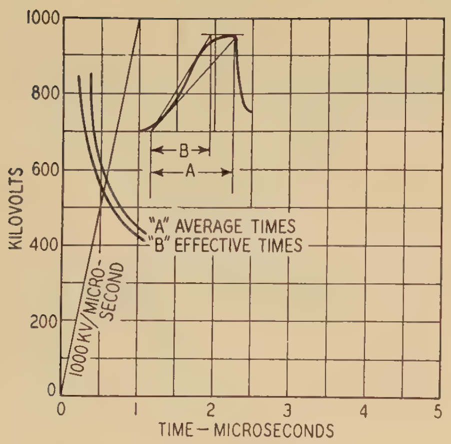


Figure 7. Data for 11-inch rod gap, showing effect of method of scaling oscillogram on time-voltage curve

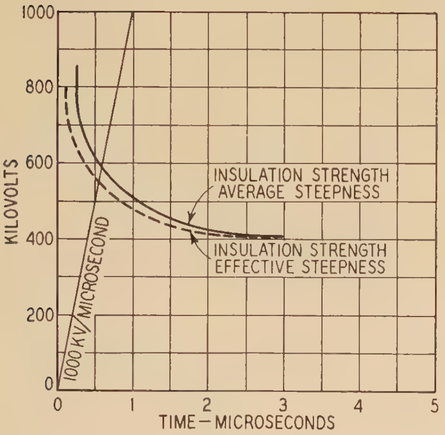


Figure 8. Data for 69-kv transformer insulation, from proposed method given in Mr. Montsinger's paper

fronts intend to use the gap as a protective device. They are not therefore, interested in voltage and time values but only in proof that the co-ordination actually works. Therefore, it is believed that it is desirable to use the gap directly and avoid the use of volt-time curves for this purpose.

There is still another suggestion, that is, that tests on sample transformers under these conditions are desirable. When the test values of 860 and 1,430 kv were proposed for 138- and 230-kv transformers respectively, transformers had been given endurance tests to see that these values could be withstood, and likewise tests with steep-wave-front waves on sample transformers are desirable before values actually withstood can be stated without question.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.) [**Editor's Note:** This discussion covers also "Corona" Voltages of Typical Transformers for Steep-Front Impulse Waves, F. J. Vogel. *EE, Jan. '38, Trans. p. 34–8.*]: These two papers comprise a valuable contribution to the better understanding of the impulse strength of material typical of that used in transformers.

It was not so many years ago that those familiar with transformer design and construction were recommending the protection of transformers with air gaps as such, or in the form of insulator strings, on the basis that the volt-time characteristic strength of the transformer insulation and the gap were essentially the same. Experience in the field and laboratory investigation soon showed definitely that this was not the case. The pendulum then swung in the opposite direction, and the transformer strength against lightning was depicted, for protection considerations at least, as being a fixed voltage value regardless of the volt-time characteristic of the lightning wave. Application of transformer protection on this basis placed heavy and perhaps unwarranted responsibility on the protective device by not utilizing the inherent strength of the transformer insulation at short time lags.

As research progressed into the more detailed characteristics of transformer insulation under impulse stresses, information which formerly had been qualitative became quantitative. We now find in Mr. Montsinger's paper definite suggestions for applying front-of-wave impulse tests at voltages considerably higher than the present full or chopped-wave tests. Such tests should demonstrate in a practical way that the short-time insulation strength which is now supposed to be built into the transformer is actually there. These suggestions, I am sure, will prove extremely valuable in setting up a test procedure for standardizing front-of-wave testing on transformers, a subject the transformer subcommittee has been actively working on for more than a year. Further, I thoroughly agree with Mr. Montsinger that front-of-wave testing be set up on a voltage and time basis which are definite units of insulation measurement rather than by specifying inches of gap, thus leaving the gap as a useful test device to chop the wave on the front, as may be specified.

Both Messrs. Montsinger and Vogel have encountered the same difficulty in carrying on their test work, namely, entrapped air in the insulation which has not received special treatment. The special treatment used by the authors, assembly under oil, vacuum treatment, tapping of the assembled sample to remove this air and thus increase the impulse strength leads directly to the question, why should it not be possible to increase the impulse strength of commercial oil-insulated transformers by admitting oil to the tank while the winding is still under vacuum? This of course leads to the next question: if this procedure were followed would it be possible in the field to change and filter the oil without breaking the vacuum, or without more than temporary reduction of impulse strength resulting from the oil change?

Could the authors give us any indication of how much, or what percentage, increase in impulse strength of transformer insulation it is possible to obtain by this oil filling under vacuum as compared with nonvacuum filling? Possible increase of insulation strength of transformers by a change of oil-filling procedure such as this may well be worth considering.

It is to be hoped the authors of both papers will continue their valuable researches on transformer insulation particularly in the short time region of the volt-time characteristic where a great deal of speculation has existed in the past, but altogether too little actually known to the point where it could be verified by test.

V. M. Montsinger: I believe the reason that Mr. Bellaschi gets a smaller difference in gap spacing for different rates of voltage rise (of, say, 750 to 1,500 kv per microsecond) than the data in my paper indicates, is because the Pittsfield gap volt-time curves probably have higher kilovolt values for short times than his volt-time curves have for the same gap spacing. In other words, the turn-up may be somewhat more. Figure 9 of this discussion shows volt-time curves of a 25-inch rod gap and a transformer winding (same shape as curve in figure 10) having an insulation level for a standard 138-kv circuit. It will be seen that there is quite a difference in their slopes which does not seem to bear out Mr. Bellaschi's expectations that once the correct schedule of gaps has been established, co-ordination for the shorter or longer waves would be established. This question is best answered by citing the results of tests made about five years ago (table III, reference 1) when a one-half inch pad of insulation

Table III

Applied Voltage (Per Cent of Full Wave)	Gap Spacing (Inches)	Kilovolts*	Time (Microseconds)
100	20.5	355	5.5
135	16.5	371	2.0
208	13.7	447	0.9
350	10.5	447	0.8
500**	6.25		0.3 (approx.)

* By sphere gap.
** Zero series resistance in generator circuit.

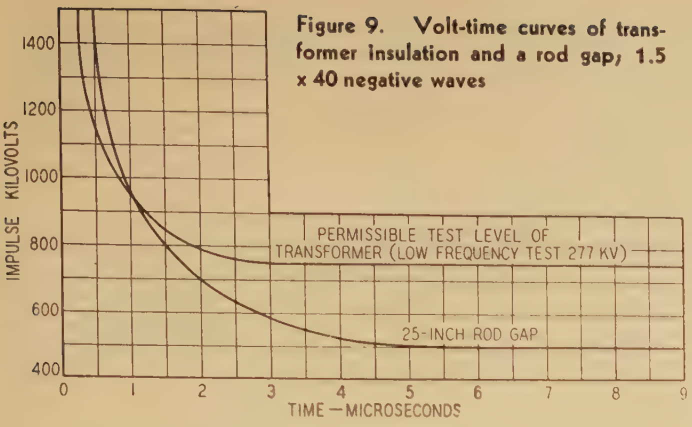


Figure 9. Volt-time curves of transformer insulation and a rod gap; 1.5 x 40 negative waves

(same as barrier *B*) was impulse tested in parallel with a rod gap.

The following tabulation shows to what extent the rod gaps had to be shortened as the wave fronts became steep by applying more and more overvoltages. In each case the gap was adjusted such that its flashover on the wave front was equal to the single-shot breakdown of the pad of insulation.

A study of the oscillograms taken at the time these tests were made shows the following results given in table III.

The above tests show conclusively that to protect even a low-voltage transformer, the gap spacing must be rapidly reduced as the wave fronts become steeper. In other words, any one gap spacing will have an impulse strength equal to the insulation over a very narrow range of time.

Mr. Gross' question about the increase in impulse strength of transformers by admitting oil to the tank with the windings under vacuum, is a difficult question to answer except in a general way. It is the air pockets entrapped in or under the insulation structures and not the air in solution (of the oil) that cause trouble. The seriousness of air pockets in series with oil and solid insulation in a highly stressed electric field can be appreciated when it is remembered that the voltage stresses are in the inverse ratio of their permittivities; i.e., the stress in volts per mil on the air, is approximately 2.2 times the stress in volts per mil on the oil and approximately 4.4 times the stress on the solid, while the dielectric strength of air is in the order of one-fourth to one-sixth that of oil and solid. Any air pockets in series with oil will, therefore, reduce the breakdown of the oil in the order of eight to ten times because when the air becomes ionized and breaks down, the oil breakdown follows. It is, therefore, out of the question to economically design transformers to withstand high impulse voltages with air pockets in the insulation under high stress.

Since the air in solution is not harmful to the dielectric strength of oil (and if the air pockets have been previously removed from the insulation) very little would be gained in the field by changing and filtering the oil under vacuum. Of course, if the oil were drained out of the transformer, air pockets most likely would be introduced when refilling. If the air pockets are adjacent to the oil in circulation under load conditions, they are absorbed in a few hours after the transformer is put in service. Their temporary presence is not harmful if the transformer has been in operation a few hours before being subjected to a high impulse voltage.

Mr. Hageguth's discussion of average versus effective rate of rise emphasizes the importance of eliminating, if possible, the bend-over of the voltage chopped by the gap. If the bend over is eliminated, and there is reason to believe it can be reduced to a negligible value by using sphere gaps to chop the wave and proper circuit constants, the question of "average rate of rise" versus "effective rate of rise" is done away with, and the testing is simplified. The reason so much space was devoted to this question in the paper was because we are at present being asked to use rod gaps to chop off the wave in front of wave testing of transformers.

Regarding Mr. Hill's discussion, the 60-cycle kilovolt values shown on figures 6, 7, and 8 are the crest values.

As to barrier *C* representing a 92-kv (185-kv low-frequency test) transformer, this barrier represents merely the type of insulation used in a 92-kv transformer. No importance should be attached to its actual kilovolt strength.

The method used in determining the initial corona was by observation—in a dark room. It is true that initial corona may not be injurious. It is more difficult to determine when corona becomes injurious than to detect initial corona. The most satisfactory method of detecting damaging corona, particularly on the coil insulation, was to lower the voltage to the highest value that previously had not shown any corona. If corona appeared it was evident that the coil insulation was damaged. Damage to the pad itself did not occur until after the insulation on the small coil was injured. Injury to the pad (if the test was continued up to this point) did not mean anything. When using bare electrodes injury to the pad had to be determined by removing from the oil and examining it for tracking.

Distribution Transformer Lightning-Protection Practice—II

By L. G. SMITH
FELLOW AIEE

TO DETERMINE the relative effectiveness of various methods of protecting distribution transformers from lightning an annual survey of operating companies was initiated in 1934 by the transmission and distribution committee of the Edison Electric Institute and continued through 1935 and 1936. In 1934 operating data were obtained from 38 companies, in 1935 from 43 companies, and in 1936 from 41 companies. The results for 1934 were presented in a previous paper. This paper presents a summary of the data for the three years and draws conclusions therefrom. It is only by collecting such data from a number of companies for numerous installations for a number of years will conclusive data be obtained so that annual variations in storm frequency and severity will be averaged. It is planned to continue the collection of these data for several years. In the future it is hoped that data for a sufficient number of years will be obtained from each company so that the troubles may be weighted by the isokeraunic level of each territory served.

Conclusions

Based upon the data collected, the following conclusions appear to be justified:

1. In so far as the rate of primary fuses blown the various protection schemes fall into the following relative order of effectiveness with not much choice among the last three named:

    First: The various methods of solid interconnection of which the solid interconnection with tie to case seems the best followed by the conventional solid interconnection and the common primary and secondary neutral schemes.

    Second: The type *SP* transformer.

    Third: The three-point connection.

    Fourth: The standard connection.

    Fifth: The gapped interconnection.

2. In protecting against transformer-winding failures the relative order of merit is not clear due to inconsistencies in the data. However, it is believed that the newer methods of lightning protection are better than the standard connection with the exception that the three-point connection and the gapped interconnection are practically no better.

3. The data indicate that lightning-arrester failure rates are lower for the types of solid interconnection and type *CSP* transformer than for the standard connection.

4. Solid interconnection does not seem to increase the number of meters burned out or troubles on customers' premises.

5. The ground resistance of lightning-arrester grounds is the most important single factor influencing the degree of lightning protection rendered. It is believed that a large part of the improvement noted by the use of solid interconnection results from the lower values of ground resistance that exist when the interconnection is made.

6. Irrespective of the type of protection the trouble rates seem to be higher for the higher distribution voltages.

7. There is no apparent trend of the effect of the type of protection upon the location of transformer-winding failures. On the average 35.2 per cent of the failures involved the primary only, 11.3 per cent involved the secondary only, and 53.5 per cent involved both the primary and secondary.

8. There seems to be a growing tendency to install secondary arresters on customers' premises.

9. It is believed that the higher the fusing schedule, the lower will be rate of primary fuses blown.

10. In the case of all types of protection a higher rate of primary fuses blown exists when the arrester is installed on the transformer side of the fuse.

11. The rates of primary fuses blown per 100 transformers are practically the same irrespective of whether one or two fuses per transformer are used.

12. The practice of grounding transformer tanks is growing.

13. The amount of attention paid to obtaining low resistance of arrester grounds is not as great as the data warrants except for solid interconnection.

Various Methods of Lightning Protection

The various protective schemes considered in this survey may be classified as follows:

1. *Standard connection* (figure 1) in which the lightning-arrester ground is not interconnected with the secondary neutral. In the case of three-phase four-wire systems the ground lead is usually tied

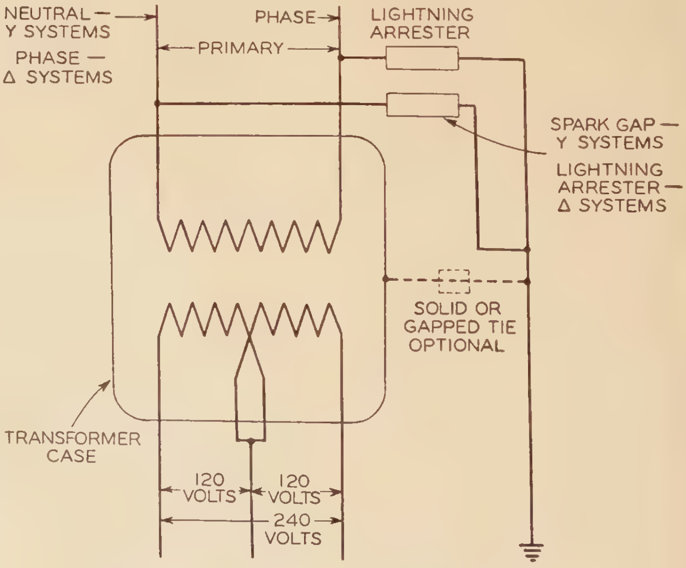


Figure 1. Standard connection

Paper number 37-111, recommended by the AIEE committee on protective devices and presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted October 20, 1937; made available for preprinting December 21, 1937.

L. G. Smith is assistant to general superintendent, Consolidated Gas, Electric Light and Power Company of Baltimore, Md.

The author wishes to acknowledge the assistance of R. D. Bader, H. C. Miller, and W. J. Witte in summarizing data for the tables, and the co-operation of the various operating companies who supplied operating data.

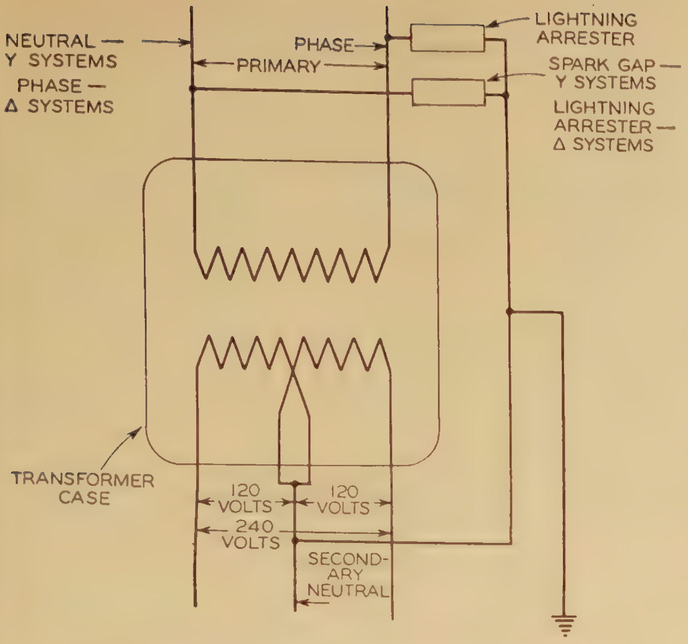


Figure 2. Solid interconnection

with the primary neutral through a gap. In some cases the transformer tank is grounded.

2. *Various types of interconnection* classified as follows:

(*a*) Solid interconnection (figure 2) in which the arrester ground lead is interconnected with the secondary neutral. The following sub-classification exists:

(1) No tie to the transformer tank (conventional type).

(2) The transformer tank tied solidly to the ground lead as in figure 3.

(3) The transformer tank tied through a gap to the ground lead as shown in figure 3.

(*b*) *Common primary and secondary neutral* (figure 6) which is obviously similar to the solid interconnection. There may be three types of this scheme as follows:

(1) Transformer tank ungrounded.

(2) Transformer tank solidly grounded.

(3) Transformer tank grounded through a gap.

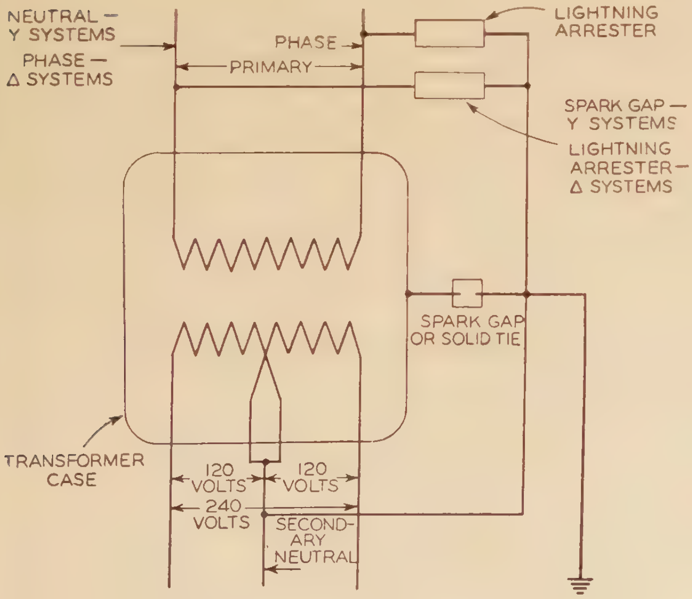


Figure 3. Solid interconnection with tie to transformer case

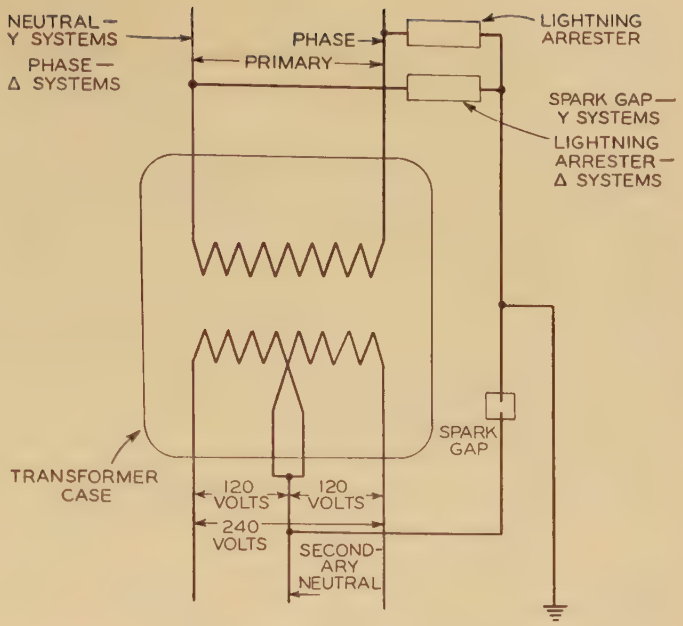


Figure 4. Gapped interconnection

(*c*) *Gapped interconnection* in which the arrester ground is interconnected with the secondary neutral through a gap. This scheme may be divided into the following subclasses:

(1) No tie to the transformer case (figure 4). The conventional type.

(2) The transformer tank tied solidly to the ground lead (figure 5).

(3) The transformer tank tied through a gap to the ground lead (figure 5).

(4) The three point connection (figure 8) in which the ground lead is connected to the tank through a gap and the arrester lead connected solidly to the tank the secondary neutral being connected to the tank through a gap.

3. *Type SP transformer* (figure 7) in which self-clearing spark gaps (deion gaps) are used instead of lightning arresters. It is essentially a gapped interconnection with the tank grounded through a gap and the connections are similar to the three-point scheme.

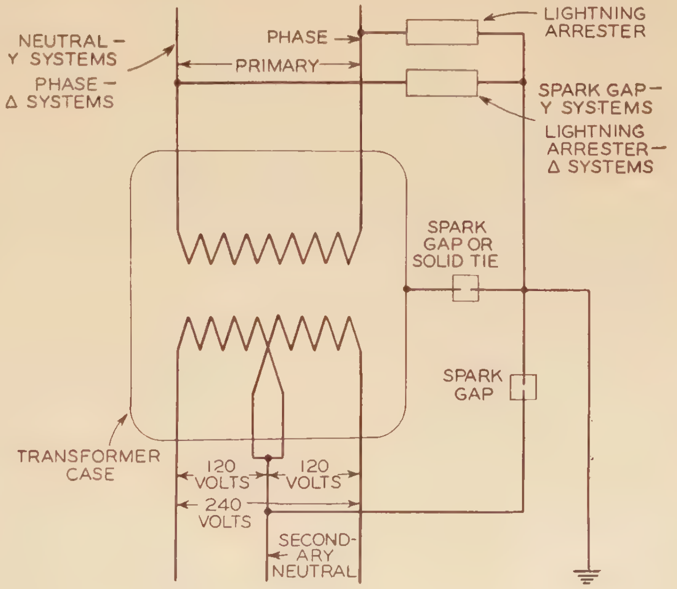


Figure 5. Gapped interconnection with tie to transformer case

Table I. Summary of Operating Data by Company and by Year

Standard Connection—Figure 1

Company	1			2				3				
Year	1934	1935	Avg.	1934	1935	1936	Avg.	1934	1935		1936	Avg
No of Installations Reported On	4150	4300	4225	3623	3221	3221	3355	5607	1177	949	6237	4657
Type of Territory By Percentages												
Urban	}100	85	}100	}100	40	44	100	}100			100	}100
Suburban		15			60	48						
Rural		0			0	8				100		
Voltage of System · KV.	4	4	4	2&4	2&4	2&4	2&4		2.3	13	2.3/13	
Phase Connection	Y	Y	Y	Δ	Δ	Δ	Δ		Δ	Y	Δ	
Fusing Schedule - %	240	240	240	200	200	200	200					
Position L A With Respect To Fuse	Line	Line	Line	Line	Line	Line	Line		Line	Line	Trans.	
Average Ground Resistance - Ohms	15	15	15	50								
Failures Per 100 Installations												
Primary Fuses Blown	13.45	3.95	8.61	0.94	3.72	5.37	3.25	2.14	6.54	17.3	6.42	5.45
Transformer Winding	0.29	1.05	0.66	0.19	0.68	0.56	0.47	0.96	0.17	0.95	1.28	1.04
Primary Only		0.88										
Secondary Only		0.17										
Primary & Secondary		0										
Lightning Arrester	0.60	2.32	1.48	0.14	0.12	0.03	0.10					
Customers' Meters Burned Out	0	2.00	1.03	0.39	0.68		0.52					
Customers' Wiring, Etc Damaged	7.08	0	3.48	0								
Grounded Tanks						No					Yes	

Company	4								6							
Year	1934	1935			1936			Avg.	1934	1935	1936			Avg.	1934	
No of Installations Reported On	5222	450	26	29	2976	1677	1457	3946	516[b]	567[b]	155[b]	392[b]	37[b]	556	18182	50
Type of Territory By Percentages																
Urban		50	0	52	100				}100	24.9	100				}100	
Suburban		30	46	3		100				67.2		100				
Rural		20	54	45			100			7.9			100			100
Voltage of System · KV.		4	6.6	11	2.3 To 13.2				4	4	4	4	4	4		
Phase Connection		Y	Δ	Δ	Δ & Y				Y	Y	Y	Y	Y	Y		
Fusing Schedule - %																
Position L A With Respect To Fuse		Line	Line	Line	60% Trans 40% Line				All on Trans. Side							
Average Ground Resistance - Ohms	25 - 200	3	40	45	20[a]	40[a]	50[a]		250	250	250	250	250	250	130	90
Failures Per 100 Installations																
Primary Fuses Blown	9.16	4.89	5.77	8.97	3.53	7.83	30.9	12.02	1.94	1.41	5.16	2.80	5.40	2.34	10.65	10.00
Transformer Winding	0.92	6.22	15.4	17.2	0.54	0.95	2.61	1.31	0.20	0.18	0	1.02	0	0.26	0.52	0
Primary Only		3.33	3.85	3.45	0.34	0.36	0.96	0.71		0	0	0	0	0		0
Secondary Only		1.11	0	3.45	0.07	0.12	0.69	0.30		0	0	0.76	0	0.26		0
Primary & Secondary		1.78	11.5	10.3	0.13	0.48	0.96	0.60		0.18	0	0.26	0	0.17		0
Lightning Arrester	0.06	7.78		0	0.27	0.66	2.75	0.82		0	0	0	0	0	3.30	
Customers' Meters Burned Out	0.11	1.78	0	0	1.21	3.34	11.8	2.34		1.06	4.50	0.76	2.70	1.48		
Customers' Wiring, Etc Damaged	0.09	3.33	0	0	0.47	0.48	0.48	0.41		0		0.26		0.10		
Grounded Tanks					Above 6.6 KV.						No	No	No			

Company	16					17						18		
Year	1934	1935		1936	Avg.	1934	1935		1936		Avg.	1936		Avg.
No. of Installations Reported On	13255	8980	1700	11095	11677	6795	5331	435	415	371	4449	1817	13	1830
Type of Territory By Percentages														
Urban		40	40	30	35	}100	100		100		}100	}100		}100
Suburban		30	30	40	35			21					100	
Rural		30	30	30	30			79		100				
Voltage of System - KV.		2.3&4	6.6	2.3-6.9	2.3-6.9		4	6.6	4	11.95	4-11.95	4	13.2	4.0&13.2
Phase Connection		Δ&Y	Δ	Δ&Y	Δ&Y		Y	Y	Y	Y	Y	Y	Y	Y
Fusing Schedule - %				300					200	200				
Position L.A. With Respect To Fuse	All on Line Side						Line	Both	Both	Both	Both	Line	Line	Line
Average Ground Resistance - Ohms	25	20	20		20-25	19.45	13	15	22	23	17	3	3	3
Failures Per 100 Installations														
Primary Fuses Blown						3.42	0.92	8.28	0.72	4.85	2.53	0.83	46.1	1.15
Transformer Winding	1.10	0.78	1.35	1.00	1.00	0.12			1.68	0.27	0.21	0.61	15.4	0.71
Primary Only									0.48	0		0.05	15.4	0.16
Secondary Only									0.24	0		0.05	0	0.05
Primary & Secondary									0.96	0.27		0.50	0	0.49
Lightning Arrester						0.34	0.17	2.95	0	1.89	0.39			
Customers' Meters Burned Out	0			0	0	0.015			0.48	0	0.04			
Customers' Wiring, Etc Damaged				0		0.47					0.47			
Grounded Tanks			Yes	Yes					Some	Some		Some	Some	Some

Company	19					20			21					
Year	1934	1935	1936		Avg.	1934	1935	Avg	1934	1935	Avg.	1934	1935	
No. of Installations Reported On	569	3095	1020	2000	2528	4700	2794	3747	124	22	73	1400	974	573
Type of Territory By Percentages														
Urban	}100	29.2	100		}100	}100	100	}100	}100	36	}100	}100	95	0
Suburban		0								0			5	40
Rural		70.8		100						64			0	60
Voltage of System - KV.		2.3-13	2.3-13		2.3-13		2.4&4			13			2.4	6.9
Phase Connection		Δ	Δ		Δ		Δ&Y			Δ			Δ	Δ
Fusing Schedule - %										1540			240	240
Position L.A. With Respect To Fuse		Line	Line	Line	Line		Line			Line			Both	Both
Average Ground Resistance - Ohms	30		25	50 To 500		35			12.2			10	20	15
Failures Per 100 Installations														
Primary Fuses Blown	8.80	5.48	2.35	10.75	6.70	2.75	1.54	2.30	4.03	4.54	4.10			
Transformer Winding	1.05	0.33	0.10	0.70	0.45	0.13	0.25	0.17	0	4.54	0.68	0.71	0.41	0.52
Primary Only									0	0	0			
Secondary Only									0	0	0			
Primary & Secondary									0	4.54	0.68			
Lightning Arrester	0.88	0.08	0	0.40	0.36	0		0	4.03	0	3.43			
Customers' Meters Burned Out	0	0	2.45	1.35	1.45	0		0	0	0	0			
Customers' Wiring, Etc Damaged	0.70	0	0	0	0.11	0		0	0	0	0	1.85		
Grounded Tanks			No	No										

Company	31				33				34				35
Year	1934	1936		Avg.	1934	1935	1936	Avg	1934	1935	1936	Avg	1934
No. of Installations Reported On	5380	551	3946	4939	4366	476	1143	1995	3362	3345	3272	3325	51
Type of Territory By Percentages													
Urban	}100	90		}100		90	75.5		100	100	100	100	
Suburban						0	0						100
Rural			95			10	24.5						
Voltage of System - KV.	4	4	11			2.4-6.6	2.3-6.6		2.3	2.3	2.3	2.3	
Phase Connection	Y	Y	Y			Δ Y	Δ&Y		Δ	Δ	Δ	Δ	
Fusing Schedule - %									240	240	240	240	
Position L. A. With Respect To Fuse		Line	Line			Both	Both		All on Line Side				
Average Ground Resistance - Ohms	30					30	30						
Failures Per 100 Installations													
Primary Fuses Blown	2.23	0	5.50	3.41	13.52	6.10	6.55	11.61	3.90	0.39	7.40	3.86	5.60
Transformer Winding	0.08	0.36	0.76	0.36	0.80	0.84	0.53	0.75	0.64	0.24	0.62	0.46	
Primary Only										0.12	0.09	0.11	
Secondary Only										0	0.03	0.15	
Primary & Secondary										0.12	0.40	0.26	
Lightning Arrester									0	0.03		0.02	
Customers' Meters Burned Out													
Customers' Wiring, Etc. Damaged													
Grounded Tanks			No				Yes				No		

Company	36				37			38				39			40
Year	1934	1935	1936	Avg	1935	1936	Avg	1934	1935	1936	Avg.	1935	1936	Avg	193
No. of Installations Reported On	4053	5314	2394	3920	3601	1856	2729	473[h]	16883	16532	11296	12951	12950	12950	2.10
Type of Territory By Percentages															
Urban	}100	60	75	}100	100	100	100	}100	50	50	}100	80	80	80	66
Suburban		20	15						50	50		10	10	10	0
Rural		20	10						0	0		10	10	10	34
Voltage of System - KV.	4	4	4	4		4		2.3&4	2.3&4	2.3&4	2.3&4	2.3-11	2.3-11	2.3-11	4
Phase Connection	Y	Y	Y	Y		Y		Δ&Y	Δ&Y	Δ&Y	Δ&Y	Δ&Y	Δ&Y	Δ&Y	Y
Fusing Schedule - %	240	240	240	240		250+									
Position L. A. With Respect To Fuse	All on Line Side					Line		Line	Line	Line	Line	Line	Line	Line	Line
Average Ground Resistance - Ohms		50	30-200	30-200	10	5	5-10	15-100	100	15-100	15-100	10	10	10	2
Failures Per 100 Installations															
Primary Fuses Blown	6.99	1.96	5.47	4.40	1.90	1.29	1.68	5.07	3.21	3.71	3.49				2.3
Transformer Winding		0.34	0.79	0.48	0.51	0.38	0.46	1.06	0.30	0.47	0.40		0.52	0.52	0.5
Primary Only															
Secondary Only															
Primary & Secondary															
Lightning Arrester		0.04	0.21	0.09		1.78	1.78		0.16	0.26	0.21				0.3
Customers' Meters Burned Out		0.04	0.13	0.07								0		0	0.0
Customers' Wiring, Etc. Damaged		0.04	0	0.03								0		0	0.0
Grounded Tanks			No							No			No		

Table I (Continued). Summary of Operating Data by Company and by Year

Standard Connection—Figure 1

	7								8	9						10[c]			
	1935			1936				Avg.	1934	1934		1935	1936		Avg	1934	1935	1936	Avg.
30	1930	7404	7336	7118	4490	3723	130	16831	4000	3575	7405	1125	811	872	4596	13000	6500	3300	7600
00	7.5 92.5	100	100	100	100	100	100	100	100	100	100	100			100	100	100	100	100
	2.3ϕ 6.6 Δ	4 Y	4 Y	4 Y	4 Y	4 Y	4 Y			4 Y 240	2.3 To 13.8 Δ 240	4 Y 240	4 Y 240	2.3 Δ 240	240	4 Y	4 Y	4 Y	4 Y
	ALL ON LINE SIDE									ALL ON LINE SIDE						LINE SIDE			
46	200	200	200				<30		70	50	60	50	1 To 200			14	14	14	14
27.7	13.3	11.3	2.33	3.88	15.3	18.98	26.9	9.74	2.75	27.4	50.3				42.7	1.11	1.07	2.82	1.35
.77	0.52	0.43	0.18	0.27	0.69	0.89	0	0.46	0.88	2.97	2.71	1.69	6.17	4.47	3.01	0.14	0.16	0.23	0.16
	0.10	0.09	0.07				0											0.03	
	0.26	0.12	0.04				0											0.03	
	0.16	0.22	0.07				0											0.18	
	4.10	4.10	0.82	0.91	4.42	3.74	6.92	2.89	0.38			3.82	3.82	6.30	4.60	0.09	0.13	0.20	0.11
									2.50								0.035	0.097	0.05
	0.26	0.14	0.03	0	0.58	0	0	0.13									0.004	0.002	0.003
				No	No	No	No						No	No				No	

13						14				15							
1934	1935	1936			Avg.	1934	1935	1936	Avg	1934	1935			1936			Avg.
1992	5500	1565	1313	1932	4107	97	100	100	99	9287	518	409	545	500	400	550[d]	4071
100	37 27 36	100	100	100	100	100	100	100	100	100	74 26 0	100	100	74 26 0	100	100	100
4 Y	4 Y	4 Y	4 Y	4 Y	4 Y	4.8 Δ 300	4.8 Δ 300	4.8 Δ 300	4.8 Δ 300		2.3 2ϕ3W	2.3 Δ	4.0 Y	2.3 2ϕ3W	2.3 Δ	4.0 Y	
ALL ON LINE SIDE						LINE SIDE					ALL ON LINE SIDE						
30	25	25	25	25	25	93.5	68	68	68 To 93.5								
0.35	1.60	0.58	0.68	3.95	1.53	19.6	14.0	32.0	21.9	7.80	2.90	6.60	2.75	3.60	9.25	7.27	7.08
0.10	0.25	0.06	0.13	0.36	0.21	1.09	0	0	0.34	3.46[e]			0				
	0.11	0.06	0	0.15	0.10		0	0					0				
	0.02	0	0	0.05	0.02		0	0					0				
	0.13	0	0.13	0.15	0.10		0	0					0				
0.15	0.15	0.26	0.19	0.31	0.20	0	7.0	0	2.36	0.33	0	0	0	0	0.50	0	0.28
0						0	1.0	0	0.34		0	0	0				
0						0	0	0	0		0	0	0				
		No	No	No				No						No	No	No	

22[f]								23						24			
1936							Avg.	1934	1935	1936			Avg	1936			Avg.
365	25	210	65	248	13	75	1516	3481	1623	260	256	71	1897	2515	2780	350	5645
100	100	100	100	100	100	100	100	100	55.0 14.4 30.6	50 20 30	0 10 90	0 0 100	100	100	100	100	100
2.3 Δ 240	2.3 Δ 240	6.9 Δ 240	6.9 Δ 240	6.9 Δ 240	12 Y 240	12 Y 240	2.4-12 Δ&Y 240		2.3&4 Δ&Y 200	4 Y 200	2.3 Δ 200	13.8 Δ 200	200	2.3 Y 200	4 Y 200	6.3 Δ 200	2.3-6.3 Δ&Y 200
INE	LINE	LINE	LINE	LINE			BOTH		LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE
10	10	7	7	7	7	7		38	38					40	40	40	40
13.75		20.65			23.05	26.65	16.68	1.15	3.21	1.54	0.39	8.45	1.81	1.87	0.90	18.0	1.45
0.10	4.00	0.48	0	0.40	0	0	0.46	0	0.25	0	0	1.41	0.11	1.07	0.65	2.86	0.98
0	0	0	0	0.40	0	0		0		0	0			0.80	0.54	2.00	0.75
0	0	0	0	0	0	0		0		0	0			0.08	0.07	0.28	0.09
0.10	4.00	0.48	0	0	0	0		0		0	0			0.20	0.04	0.57	0.14
								0.03	0.12				0.06	0.68	0.29	3.43	1.56
								0	0.06	1.15			0.07				
								0	0				0				
No	No	No	No	No	No	No	No			No	No	No		No	No	No	No

25	26					27			28			29				30			
1934	1934	1936			Avg.	1934	1935	Avg	1935	1936	Avg.	1934	1935	1936	Avg	1934	1935	1936	Avg
1500	4500	2050	2050	180	4390	14500	8010	11255	8	19[g]	14	5200	3300	8277	5592	16172	13850	7850	12624
100	100	100	100	100	100	100			100	80 20 0	100	100		75 15 10	100	100	100	100	100
	4 Y	4 Y	4 Y	4 Y	4 Y		2.4 Δ		4 Y	4 Y	4 Y		4&6.6 Y&Δ 200	4&6.9 Y&Δ 250	4&6.9 Y&Δ 250	4.8 Δ	4.8 Δ 300	4.8 Δ 250	4.8 Δ 250
	LINE	LINE	LINE	LINE	LINE		TRANS		LINE SIDE				LINE	LINE	LINE	LINE	LINE	LINE	LINE
12	80	75	75	75	75				75	70	70-75	30	20	20	20-30	15	10	0+	10
		1.90	5.76	7.23	3.97				0	0	0	5.76	7.15	5.15	5.74	2.72	1.01		1.93
	2.44	0.83	3.66	4.44	2.39	0.25	0.19	0.23	0	0	0	0.39	0.64	2.46	1.46	0.16	0.12	0.36	0.19
		0.05	0.20	0.56	0.14				0	0	0		0.39				0.03	0.04	0.03
		0	0.20	0.56	0.12				0	0	0		0.12	0.28			0	0	0
		0.78	3.26	3.33	2.08				0	0	0		0.12				0.09	0.32	0.17
		0.15	0.34	0	0.23				0	0	0			0.02	0.02	2.17	0.95		1.61
		0.05	0.58	2.78	0.42							0.25			0.25				
												0.29	0		0.18				
		No	No	No					SOME	YES				No				SOME	

42	43	44			45	47	50					55
1935	1935	1935	1936	Avg	1936	1935	1935		1936		Avg	1936
13638	6000	300	1217	758	4071	689	1651	1318	1542	1220	2866	315
	67 0 33	0 0 100	100	100	80 20	5 35	100 0 0	55.5 0 44.5				100
2.4-12 Δ&Y	2.4-6.6 Δ&Y 200	11.5 Y 450	4 Y 450	4&11.5 Y 450	2.3-6.9 Δ&Y	2.4-11 Δ&Y	2.4 Y	6.6 Y	4 Y 250	12 Y 250	2.4-12 Y 250	2.3-6.9 Δ&Y
LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE
		13	20-25				17	17	16.5	16.5	17	28
4.01	3.55	10.70	2.22	3.89	8.85	15.1	3.51	2.17	3.05		8.65	14.29
0.24	0.62	0.67	0.16	0.26	0.81	0.58	1.57	0.46	1.36	0.41	1.01	1.27
	0.05					0.58	1.09	0.38	0.71	0.16	0.63	
	0.02					0	0.12	0	0.13	0	0.07	
	0.55					0	0.36	0.08	0.52	0.25	0.31	
	0.44				0.20							
		0			3.64	0	0	0	0	0	0	1.90
		0				0	0	0			0	
			No		No				No	No		

67					68	69			70					
1935	1936			Avg	1935	1935	1936	Avg	1936					Avg
363	1284	985	172	1404	10000	15	12	14	84	10	45	94	98	331
	100	100	100	100		100	100	100	100	100	100	100	100	100
2.4 Δ 400	2.3 Δ	2.3 Δ	2.3 Δ	2.3 Δ	250	4.8 2ϕ4W	4.8 2ϕ4W	4.8 2ϕ4W	2.3 Δ	2.3 Δ	2.3 Δ	6.9 Δ	6.9&13.8 Δ 230	2.3-13.8 Δ
LINE	LINE	LINE	LINE	LINE	TRANS	TRANS	TRANS	TRANS					LINE	
	668	668	668	668	25 50									
4.68	0	8.19	18.02	4.60		0	8.33	3.70	15.49	10.00	6.67	2.13	6.13	13.0
1.10	0.08	0.51	0.58	0.33	0.59	0	0	0						
0.55	0.08	0	0.58	0.14	0.07	0	0	0						
0	0	0.20	0	0.07	0.03	0	0	0						
0.55	0	0.30	0	0.18	0.49	0	0	0						
0.28	0	0	0.58	0.07		0	0	0			2.22			
0	0	0.10	0	0.04		0		0	2.38			1.06		1.65
0						0		0						
	No	No	No				No		No	No	No	No	No	No

a. Covers 45% of Installations.
b 3ϕ Transformers.
c Failures per 100 Installations taken from Company rates
d 550 3ϕ Transformers.
e Includes both bushing and winding.
f Installation total includes a few interconnected transformers However, all failures were on Standard Connection
g No Spark gap used.
h 3 Years

Table II. Summary of Operating Data by Company and by Year

Solid Interconnection—Figure 2

Company	2				4									6°						7				8	
Year	1934	1935	1936	Avg	1934	1935				1936			Avg.	1934	1935	1936			Avg.	1934	1935	1936	Avg	1934	1934
No. of Installations Reported On	3708	9051	15971	9577	502	90	546	25	25	693	253	215	783	4652	5031	1154	3404	612	4951	28	853	1521	801	154	3536
Type of Territory by Percentages																									
Urban		80	73			70		0	0	100					21.8	100									
Suburban	}100	20	17	}100	100	0		50	50		100		}100	}100	62.7		100		}100					}100	}100
Rural		0	10			30		50	50			100			15.5			100		100	100	100	100		
Voltage of System - KV.	2 & 4	2 & 4	2 & 4	2 & 4	2.3	2.3	2.3	11	13	2.3 & 4	2.3 & 4	2.3 & 4	2.3-13	4	4	4	4	4	4	4	4	4	4		
Phase Connection	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ & Y	Δ & Y	Δ & 4	Δ & Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Δ
Fusing Schedule - %	200	200	200	200						250	250	250	250												
Position L.A. With Respect To Fuse	Trans	Trans	Trans	Trans		Trans	Both	Line	Line	80%	Trans	20% Line	Both	Trans	Trans	Trans	Trans	Trans	Trans	Line	Line	Line	Line		
Average Ground Resistance Ohms	3				25	29.7	4.5	15	15	4	6	6		5	6.7	6.7	6.7	6.7	6	8.7	25	2		70	120
Failure Data Per 100 Installations																									
Primary Fuses Blown	0.94	1.67	2.68	2.13	19.5	1.11	4.58	0	0	3.03	10.69	4.19	7.70	1.58	0.86	0.26	1.97	2.46	1.32	0	3.64	5.05	4.50		32.5
Ratio-Change over Std. Connection-%	100.0	44.9	49.9	65.5	213	2.27	9.37	0	0	85.8	136.3	13.5	64.0	81.5	61	5.03	70.3	45.4	56.4	0	32.2	29.5	46.2		64.2
Transformer Winding	0.14	0.34	0.36	0.32	0.40	0	0.18	0	0	0.29	0.40	0	0.25	0.16	0.22	0.35	0.18	0	0.19	0	0.47	0.86	0.71		1.73
Ratio Change over Std. Connection-%	69.9	50.0		68.0	43.5	0	2.89	0	0	53.8	42.1	0	19.1	80.5	122	∞	17.6	*	73.0	0	109	112	157		63.9
Primary Only						0	0.18	0	0	0.29	0	0	0.16		0	0.09	0.09	0	0.04	0	0.12				
Ratio Change over Std. Connection-%						0	5.40	0	0	85.3	0	0	22.5		*	∞	∞	*	∞		133				
Secondary Only						0	0	0	0	0	0	0	0		0.04	0	0.03	0	0.03	0	0.12				
Ratio Change over Std. Connection %						0	0	0	0	0	0	0	0		∞	*	3.94	*	12.5		100				
Primary & Secondary						0	0	0	0	0	0.40	0	0.05		0.18	0.26	0.06	0	0.14	0	0.23				
Ratio Change over Std. Connection %						0	0	0	0	0	83.3	0	8.33		100	∞	23.1	*	80.4		104				
Lightning Arrester	0	0.55	0.04	0.20	0	0	1.46	0		0.28	1.19	3.72	0.90		0.38	0.17	0.21	0.49	0.30	3.37	0.94	0.86	0.92		
Ratio Change over Std. Connection %	0	438	133	195	0	0	18.75	*		104.0	180.5	135.2	110.0		∞	∞	∞	∞	∞	102.1	22.9	20.7	31.8		
Customers' Meters Burned Out	0.32	0.57		0.50	0.40	0	0	0		0.43	0	0.47	0.26			1.38	2.46	0.65	2.01						
Ratio Change over Std Connection %	83.7	83.9		96.1	363	0	0	*		36.0	0	4.06	11.10			30.6	324	24.1	136						
Customers' Wiring, Etc. Damaged	0				0.40	0	0	0		1.01	0	0	0.39		0.68	3.29	0.35	0.16	0.83		0.23	0.66	0.51		
Ratio Change over Std. Connection %	*				444	0	0	*		215	0	0	0.95		∞		135		830		164	212	381		

Company	20	21				23				24	28			29			30				31	32	33		
Year	1934	1934	1936		Avg.	1934	1935	1936	Avg.	1936	1935	1936	Avg	1934	1935	Avg	1934	1935	1936	Avg.	1934	1934	1934	1935	1936
No. of Installations Reported On	1300	4582	134	18	2367	1919	2175	2757	2284	10	38	33	56	20	20	20	29760	36300	34589	33550	50	6851	866	813	411
Type of Territory by Percentages																									
Urban			100			100	100	98		100		80			55			77	0		100		100	100	93.9
Suburban	}100	}100			}100			2	}100		}100	20	}100	}100	45	}100	}100	}92.3	}100	}100		}100			0
Rural				100				0							0										6.1
Voltages of System - KV			13	13		4	4	4	4	2.3 & 4	4	4	4	4-6.6	4-6.6	4-6.6	4.8	4.8	4.8	4.8				2.4-6.6	[illegible]
Phase Connection			Y	Y		Y	Y	Y	Y	Δ & Y	Y	Y	Y	Y-Δ	Y-Δ	Y-Δ	Δ	Δ	Δ	Δ				Δ	Δ & Y
Fusing Schedule - %			250	250		200	200	200	200	200				200	200	200	300	300	250	300					
Position L.A With Respect To Fuse			Line	Line		Trans.	Trans	Trans	Trans	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line				Both	Both
Average Ground Resistance - Ohms	0.25	9.8				1	1	2	1-2		10	10	10	1.9	2	2	10	10	12	10-12		1	30		30
Failure Data Per 100 Installations																									
Primary Fuses Blown	1.46	0.15	1.49	0	0.19	0.10	1.20	0.22	0.30		0	0	0	0	0	0	2.79	1.39		2.02		0.51	1.50	4.68	2.92
Ratio Change over Std Connection-%	53.1	3.72	†	†	4.63	9.04	37.4	14.3	27.6		*	*	*	0	0	0	102.5	138		105		†	11.1	76.8	44.5
Transformer Winding	0.08	0	0	0	0	0.05	0.05	0.04	0.04		0	0	0	0	0	0	0.47	0.15	0.46	0.35		0.09	0.12	0.12	0.24
Ratio Change over Std Connection-%	62.5	*	†	†	0	∞	20.0	∞	40.0		*	*	*	0	0	0	308	125	128	189		†	14.5	14.3	45.3
Primary Only		0	0	0	0						0	0	0	0	0	0		0.06	0.13	0.10					
Ratio Change over Std. Connection - %		*	†	†	*						*	*	*	0	0	0		200	325	297					
Secondary Only		0	0	0	0						0	0	0	0	0	0		0.02	0.03	0.02					
Ratio Change over Std Connection-%		*	†	†	*						*	*	*	0	0	0		∞	∞	∞					
Primary & Secondary		0	0	0	0						0	0	0	0	0	0		0.07	0.30	0.182					
Ratio Change over Std. Connection %		*	†	†	0						*	*	*	0	0	0		77.8	93.7	107					
Lightning Arrester	0	0.07	0	0	0.06	0	0.14	0.07	0.07		0	0	0	0	0	0	2.39	1.38		1.83		0.61			
Ratio Change over Std. Connection %	*	1.64	†	†		0	117		122		*	*	*		0	0	110	145		114		†			
Customers' Meters Burned Out	0	0	0	0	0	0	0.09	0.11	0.07					0	0	0		0		0	0	0.15			
Ratio Change over Std Connection%	*	*	†	†	*	*	150	9.55	98.7					0	0	0						†			
Customers' Wiring, Etc. Damaged	0	0	0	0	0	0								0	0	0		0		0	0	0			
Ratio Change over Std. Connection-%	*	*	†	†	*	*								0	*	0						†			

4. *Type CSP transformer* (figure 9) which is similar to the type *SP* transformer except a secondary breaker is used and a high-rating fuse link is installed in the transformer. The intention is that no primary fuse be used.

In each of the protection schemes described, except the type *SP* and *CSP* transformers, the primary fuse or fuses may be installed on either the line or transformer side of the lightning arresters. On three-phase four-wire systems except for type *SP* and *CSP* transformers the lightning arrester ground is interconnected with the primary neutral usually through a gap whereas on three-wire systems two arresters and primary fuses are used. These alternatives are indicated on figures 1 to 5 and 8.

Operating Results 1934–1935–1936

Detail Data by Companies

While the data collected have been summarized to draw various comparisons in the tables of this paper it is believed the principal value of a paper of this type is to include the detail data submitted by each operating company so that the information can be set up to draw

Table II (Continued). Summary of Operating Data by Company and by Year

Solid Interconnection—Figure 2

9					10				12
1936				Avg.	1934	1935	1936	Avg	1935
7618	559	2344	857	12082	21000	26167	30614	25927	2847
85	0	10	10			100	100		
15	20	20	20	}100	}100			}100	}100
0	80	70	70						
4	4.8&8	6.9	11.5&18.8	2.4&13.8	4	4	4	4	4
Y	Δ&Y	Y	Δ&Y	Δ&Y	Y	Y	Y	Y	Y
					Line	Line	Line	Line	Line
20	50	50	50		0.5	0.5	0.2	<0.5	
					0.38	0.39	0.76	0.51	0.49
					26.5	36.4	26.9	37.9	†
0.91	1.43	2.51	7.47	1.34	0.07	0.09	0.13	0.10	0.11
148				44.5	47.9	58.1	36.1	63.5	†
							0.02	0.02	0.07
							800	80.0	†
							0.02	0.02	0.04
							96.4	96.4	†
							0.08	0.08	0
							46.5	46.5	†
	0				0.141	0.13	0.25	0.18	0.17
	0				164.1	101.0	124	159	†
7.34						0.06	0.09	0.08	0.36
						171.5	34.9	151.0	†
						0.003	0.001	0.001	0
						62.5	50.0	46.7	†

13						14				15			
1934	1935	1936			Avg	1934	1935	1936	Avg.	1934	1935	1936	Avg
1934	4380	898	2846	309	3456	97	100	99	99	4143	2165	2150°	2819
	15	100									100	100	
	70		100		}100					}100			}100
}100	15			100		100	100	100	100				
4	4	4	4	4	4	4.8	4.8	4.8	4.8	2.4	2.4	2.4	2.4
Y	Y	Y	Y	Y	Y	Δ	Δ	Δ	Δ	2φ3W	2φ3W	2φ3W	2φ3W
						300	300	300	300				
Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line
2	3	2	2	2	2	22.8	17	17	17-23				
0.15	0.41	0.22	0.35	0.13	0.36	10.00	10.00	18.20	12.82	0.94	0.60	0.56	0.76
44.1	25.6	37.9	51.5	3.19	23.5	32.5	71.4	56.9	58.5	12.0	20.7	15.6	10.7
0.103	0.11	0	0	0	0.07	1.03	0	0	0.34	0.60	0.42	0.05	0.41
103	44	0	0	0	32.9	100	*	*	101	17.3			
	0.02	0	0	0	0.01		0	0	0				
	182	0	*	0	10.3		*	*	*				
	0.05	0	0	0	0.02		0	0	0				
	250	*	*	0	105		*	*	*				
	0.05	0	0	0	0.02		0	0	0				
	38.4	*	0	0	20.6		*	*	*				
0.15	0.16	0.11	0.14	0	0.14	1.03	6.00	0	2.36	0.05	0.65	0.05	0.20
102	107	55.0	73.7	0	71.7	∞	85.7	*	100	14.5	∞	∞	96.5
0		0	0	0	0	0	0	0	0	0.37			0.37
*						*	0	*	0				
0		0	0	0	0	0	0	0	0				
*						*	*	*	*				

16				17				18	19				
1934	1935	1936	Avg	1934	1936		Avg	1934	1934	1935	1936		Avg
900	2340	3668[c]	2303	9	79	2	45	427	144	235	300	53	244
	60	30			100			100		81.2	100		
	20	40	}100	}100			}100		}100	0			}100
	20	30				100				18.8		100	
	2.4&4.4	2.4, 4.4 & 4	2.4-4.6		4	12		4.4&13.2		2.4	2.3-13.8	2.3-13.8	
	Δ&Y	Δ&Y	Δ&Y		Y	Y		Y		Δ	Δ&Y	Δ&Y	
		300			200	200							
	Line	Line			Trans.	Trans.		Line		Line	Line	Line	
25	20			10.5	1-5	1-5		3	30				
					1.27		1.27	0.47	5.6	2.55	1.67	18.85	3.83
					176		50.1	40.9	63.6	46.5	71.0	175	57.1
	0.21	1.09	0.75		1.27	0	0.12	0.7	2.78	0	0	0	0.55
	26.9	109	75		75.6	0	57.0	98.5	264	0	0	0	81.8
					1.27	0	0.12			0	0	0	0
					265	*				0			
					0	0	0			0	0	0	0
					0	*				0			
					0	0	0			0	0	0	0
					0	0				0			
					3.8	0	0.37	0	1.39	0.43	0	1.89	0.55
					∞	0	94.9		158	538	*	472	133
0		0	0	0	0	0	0	0	0	0			0
*		*	*	0	0	*	0		0	0			0
0		0	0	0				0	0	0	0	0	0
		*		0					*	0	*	*	0

34				36				37			40	42	45
1934	1935	1936	Avg	1934	1935	1936	Avg	1934	1935	Avg	1935	1935	1936
41	40	38	40	11122[a]	11438	13227	12596	2063	2772	2418	1900	1885	1278
100	100	100	100		40	40		100	100	100	100		100
				}100	60	60	}100						
					0	0							
2.3	2.3	2.3	2.3	4	4	4	4	4	4	4	4	2.4-12	2.3
Δ	Δ	Δ	Δ	Y	Y	Y	Y	Y	Y	Y	Y	Δ&Y	Δ
230	230	230	230	230	230	230	230	250	250	250			
Trans.	Trans.	Trans.	Trans.	Line	Line	Line	Line	Line	Line	Line	Trans.	Line	Line
0	0	0	0		0.5	0.2		10.0	5.0	5-10	1.0		
4.88	5.00	7.90	5.88	2.37	0.56	1.11	1.32	1.02	0.25	0.58	1.00	4.30	1.88
125	1280	107	152	339	28.6	20.3	30.0	58.7	19.4	34.5	42.1	107	21.2
0	0	0	0		0.11	0.13	0.12	0.30	0.14	0.21	0.16	0.27	0.16
0	0	0	0		32.4	16.4	25.0	57.7	36.8	45.0	28.1	112	19.7
0	0	0	0								0.11		
	0	0	0										
0	0	0	0								0		
	*	0	0								0		
0	0	0	0								0.06		
	0	0	0										
0	0		0		0.10	0.12	0.11		0.50	0.50	0.16		0.31
*	0		0		250	57.1	121		28.1	28.1	48.5		148
					0.01	0.03	0.02				0		5.87
					25.0	23.1	33.8				0		161
					0	0	0				0		
					0	*	0				0		

50					51			55	69		
1935		1936		Avg.	1936		Avg.	1936	1935	1936	Avg
360	5	497	555[e]	709	2179	2037	4216	59	392	403	398
100	100										
					}100		}100		100	100	100
						100		100			
6.6	2.4	12	12		4	12		2.3&4.4	4.8	4.8	4.8
Y	Y	Y	Y		Y	Y		Δ&Y	2φ4W	2φ4W	2φ4W
					240	240	240				
Line	Trans.	Line			Trans.	Trans.	Trans.	Line	Trans.	Trans.	Trans.
17	17				4	10		28	14.1	14.1	14.1
	0		0		1.14	6.30	3.62	1.70	13.5	3.22	8.30
	0				†	†	†	11.9	∞	38.6	224
0.83	0	1.01	0.18	0.64	0.09	0.20	0.14	0	0.31	0.25	0.38
180	0	246	44.0	62.9	†	†	†	0	∞	∞	∞
0.28	0	0.40	0	0.21	0	0.10	0.06	0	0	0	0
73.8	0	250	0	38.7	†	†	†		*	*	*
0.55	0	0.60	0	0.253	0	0	0	0	0.25	0.25	0.25
∞	0	∞	*	504	†	†	†		∞	∞	∞
0	0	0	0.18	0.07	0.09	0.10	0.10	0	0.25	0	0.13
0	0	0	72.0	22.6	†	†	†		∞	*	∞
	0				0.64	1.08	0.85		1.79	0.50	1.13
	0				†	†	†		∞	∞	∞
0	0	0		0	0.05	0.05	0.06	0	1.28		1.28
*	*	*		*	†	†	†	0	∞		∞
0	0				0	0	0	0	0.51		0.51
*	*				†	†	†		∞		∞

* No failures either connection.
† Standard Connection not used.
a Not directly comparable with Fig. 1.
b Lightning arrester used on each wire.
c Includes some Gapped Interconnection
d Includes some Gapped Interconnection
e Spillgap used instead of lightning arr.

any comparison desired. The data submitted by each company for the three-year period have been included in tables I to IX. Each table covers a type of protection. All failures and primary fuses blown are those attributed to lightning. All rates of trouble are the number per 100 transformer installations. Primary fuses blown are exclusive of those blown by arrester or transformer failures.

Comparison of Various Schemes of Protection

In tables X, XI, and XII the data have been summarized for the three years. Since in 1935 and 1936 the data was obtained in more detail, tables XIII, XIV and XV have been prepared covering average data for these two years. Since the reports for many companies did not segregate operating data by types of territory tables X and XIII represent a greater number of installations than the sum of those represented in the component tables covering rural and more thickly populated territories. In the summary tables, i.e., X to XXIV, the average number of transformer installations in each case is the average of the total installations for the years covered in each table. However, the trouble rate for

Table III. Summary of Operating Data by Company and by Year

Solid Interconnection With Tie to Case—Figure 3

Company	3	4						11			13	16			18	33		
Year	1935	1934	1935			1936	Avg.	1935	1936	Avg.	1936	1935	1936	Avg.	1936	1935	1936	Avg.
No. of Installations Reported On	103	35	7	514	31	58	215	1477	1500	1489	103	570	916^a	743	28	45	79	62
Type of Territory by Percentages																		
Urban	100			48	0		}100	100	100	100		30	20	}100		100	82.3	88.7
Suburban		}100		17	39							50	30		100		0	0
Rural			100	35	61	100					100	20	50				17.7	11.3
Voltage of System - KV.	4	11&13.2	2.4	2.4	11	2.3-13.2		2.4	2.4	2.4	4	6.9	6.9	6.9	13.2	2.4-6.6	2.4-12	
Phase Connection	Y	Δ	Δ	Δ	Y	Δ&Y		2φ4W	2φ4W	2φ4W	Y	Δ	Δ	Δ	Y	Δ&Y	Δ&Y	
Fusing Schedule - %						300							300					
Position L.A. With Respect To Fuse	Line		Trans	Line	Trans	Both		Line	Line	Line	Line	Line	Line	Line	Line		Both	
Average Ground Resistance - Ohms		20	56		133	10		0.10	0+	0+	2	20			0.5		30	
Failure Data Per 100 Installations																		
Primary Fuses Blown	4.85	22.8	0	6.03	0	24.15	8.22	0.07	0	0.03	0.97				50.0		5.06	5.06
Ratio-Change over Std. Connection-%	74.2		0	12.3	0	78.0	68.3	†	†	†	24.6				108		77.3	435
Transformer Winding	0.97	14.3	0	1.36	0	0	1.86	0	0	0	0	0.53	0.11	0.37	7.15	0	1.27	0.81
Ratio Change over Std. Connection-%	5.70		0	21.8	0	0	1.42	†	†	†	0	39.3	11.0	37.1	46.5	0	240	107
Primary Only			0	0.39	0	0	0.33	0	0	0	0					0		
Ratio Change over Std. Connection-%			0	11.7	0	0	46.2	†	†	†	0							
Secondary Only			0	0.39	0	0	0.33	0	0	0	0					0		
Ratio Change over Std. Connection-%			0	35.2	0	0	1092	†	†	†	0							
Primary & Secondary			0	0.58	0	0	0.49	0	0	0	0					0		
Ratio Change over Std. Connection %			0	32.6	0	0	82.0	†	†	†	0							
Lightning Arrester		0	0	0.19	0	0	0.16	0	0	0	0							
Ratio Change over Std. Connection-%			0	2.44	*	0	18.9	†	†	†	0							
Customers' Meters Burned Out		0	0	0	0	0	0	0	0	0	0		0	0				
Ratio Change over Std Connection-%			0	0	*	0	0	†	†	†			*	*				
Customers' Wiring, Etc. Damaged		5.72	0	0	0	0	0.31	0	0	0	0		0	0				
Ratio Change over Std. Connection-%			0	0	*	0	75.6	†	†	†			*					
Tie to Case - Solid(S) or Gapped(G)	S	S	S	G	G	Both	Both	S	S	S	S	S	Both	Both	S	G	G	G

* No failures either connection.
† Standard Connection not used.

a. Includes some Gapped Interconnection with Tie to Case.

Table IV. Summary of Operating Data by Company and by Year

Gapped Interconnection—Figure 4

Company	1	4							6^a						7	13	14				19					
Year	1935	1935			1936			Avg	1934	1935	1936			Avg.	1936	1936	1934	1935	1936	Avg	1934	1935	1936		Avg.	
No of Installations Reported On	1000	573	23	89	191	150	690	858	646	707	17^b	434^b	291^b	698	883	260	98	101	101	100	72	998	50	1220	780	199
Type of Territory by Percentages																										
Urban	0	7		3	100					2.0	100												100		21.3	15
Suburban	30	5		10		100		}100	}100	50.2		100		}100												60
Rural	70	88	100	87			100			47.8			100		100	100	100	100	100	100	100	100		100	78.7	25
Voltage of System - KV	4-12	2.4	7.6	13	2.3-13.2	2.3-13.2	2.3-13.2	2.3-13.2	4	4	4	4	4	4	4	4	4.8	4.8	4.8	4.8	2.4-13.8	2.4-13.8	2.4-13.8	2.4-13.8	2.4-13.8	4
Phase Connection	Y	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Y	Y	Y	Y	Y	Y	Y	Y	Δ	Δ	Δ	Δ	Δ&Y	Δ&Y	Δ&Y	Δ&Y	Δ&Y	Y
Fusing Schedule - %					250	250	250										300	300	300	300						200
Position L.A. With Respect To Fuse	Line	Both	Both	Trans	Both	Both	Both	Both	Trans	Trans	Trans	Trans	Trans	Trans	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line	Trans
Average Ground Resistance - Ohms	15	90	60	20	25	50	50	58	5	250	250	250	250	174	2	25	101	75	75	83	30					10
Failure Data Per 100 Installations																										
Primary Fuses Blown	3.50	10.1	4.35	58.5	10.5	28.0	10.0	14.10	3.13	1.27	5.89	3.69	3.44	2.68	3.96	1.92	9.2	13.9	22.8	15.33	7.20	3.91	8.00	7.37	5.90	3.02
Ratio Change over Std Connection-%	88.6	20.7	7.54	65.2	298	338	324	117	161	90.0	114	132	63.7	114	23.2	48.5	470	99.2	72.2	70.0	81.8	71.4	340	68.5	88.1	196
Transformer Winding	0.70	0.35	4.35	0	0.32	1.33	1.01	0.76	0.16	0.14	0	0.92	0	0.29	0.45	0	0	1.98	1.98	1.33	0	0.10	0	0.74	0.43	0
Ratio Change over Std Connection-%	66.6	5.62	28.2	0	97.0	140	38.7	58.0	78.0	77.8	*	90.1	*	110	58.5	0	0	∞	∞	396	0	30.3	0	106	95.2	*
Primary Only	0.60	0.35	4.35	0	0	0.67	0.58	0.47		0	0	0.46	0	0.14		0	0	0.99	0.99	0.66	0					0
Ratio Change over Std. Connection-%	68.2	10.5	113	0	0	186	60.5	66.2		*	*	∞	*	∞		0		∞	∞							*
Secondary Only	0.10	0	0	0	0	0	0.15	0.06		0.14	0	0	0	0.07		0	0	0	0	0	0					0
Ratio Change over Std Connection-%	62.5	0	*	0	0	0	21.0	20.0		∞	*	0	*	26.6		0		*	*							*
Primary & Secondary	0	0	0	0	0.32	0.67	0.29	0.23		0	0	0.46	0	0.14		0	0	0.99	0.99	0.66	0					0
Ratio Change over Std Connection-%	*	0	0	0	388	139.0	30.2	384		0	*	177	*	79.3		0		∞	∞							*
Lightning Arrester	4.00	2.10	0	13.5	2.62	1.33	0.72	2.10		0.42	0	0.69	0.34	0.48	0.23	0.38	0	3.96	0	1.33	1.39	0.30	2.00	0.57	0.51	0
Ratio Change over Std Connection-%	172	270	0	∞	970	198	26.2	256		∞	*	∞	∞	∞	7.80	123	*	56.6	*	56.3	158	375	∞	143	149	
Customers' Meters Burned Out	0.20	2.62	0	13.5	4.19	4.66	2.03	3.26								0	0	0	0	0	0	0				0
Ratio Change over Std. Connection-%	10.0	147	*	∞	346	140	17.2	27.6									*	0	*	0	*	*				0
Customers' Wiring, Etc Damaged	0	0	0	0	0	0	0.15	0.06		0.28	0	0.46	0	0.28	0.11	0	0	0	0	0	0	0				
Ratio Change over Std Connection-%	*	0	*	*	0	0	30.2	12.5		∞		177		276	35.5		*	*	*	*	0	*				

* No failures either connection
† Standard Connection not used.

a Not directly comparable with Fig. 1

b Lightning Arrester used on neutral

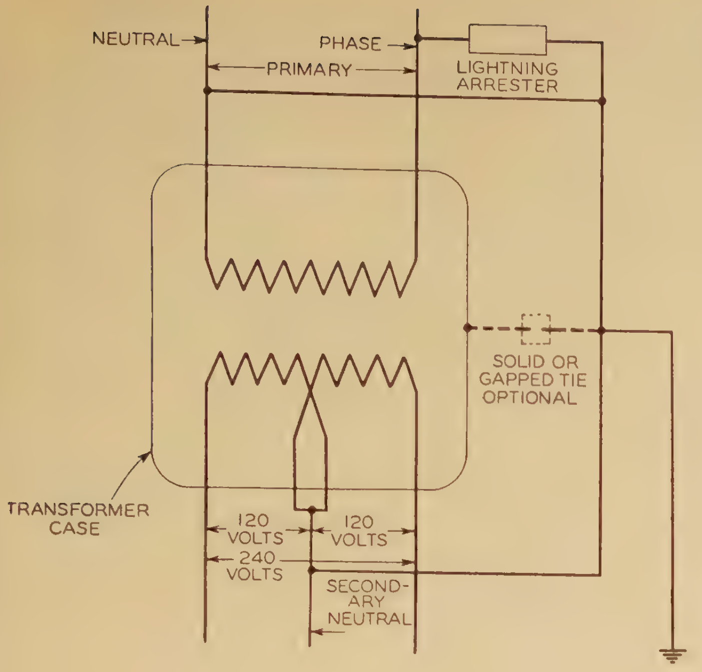


Figure 6 (left). Common primary and secondary neutral

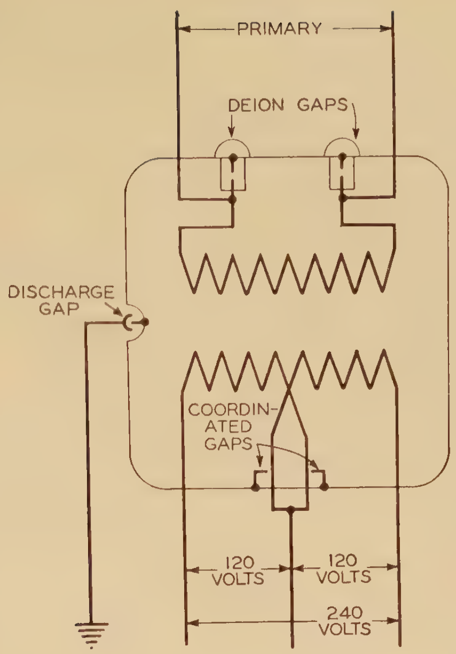


Figure 7 (right). Surge-proof transformer

each item of trouble is determined by taking the sum of troubles for each item for the period under consideration as a percentage of the sum of the installations on which data were reported for that item. Since very few companies failed to supply data for primary fuses blown, transformer winding failures, and lightning arrester failures, the trouble rate in each of these cases may be considered as based upon the average of the total number of installations shown in the tables. However in the case of the segregation of the location of transformer winding failures, a number of companies did not supply segregated data. Therefore, the sum of the segregated rates will not equal the total rates of transformer winding failures.

In comparing the relative *rates of primary fuses blown* using the various protective schemes, a study of tables X to XV shows that the schemes using solid interconnection show the lowest rate of primary fuses blown using any of the six bases of comparison. Where sufficient data is available to compare the conventional solid interconnection, the interconnection with tie to transformer tank; and the common primary and secondary neutral,

Table IV (Continued). Summary of Operating Data by Company and by Year

Gapped Interconnection—Figure 4

3	3	26	26	26	33	33	33	34	34	34	34
	Avg.	1936	1936	Avg	1935	1936	Avg	1934	1935	1936	Avg
9	284	660	350	1010	2543	2419	2481	57	58	53	56
						18.3	8.9	100	100	100	100
	}100	100				0					
100			100	}100	100	81.7	91.1				
13.8		4	4	4	24-46	23-12	23-12	2.4	2.4	2.4	2.4
Δ		Y	Y	Y	Δ	Δ & Y	Δ & Y	Δ	Δ	Δ	Δ
200	200							240	240	240	240
Trans	Trans	Line	Line	Line	Both	Both	Both	Line	Line	Line	Line
10	10	75	75	75		30		0			
11.1 131	2.46 136	1.06 18.4	8.86 123	3.76 94.7	8.26 135	7.86 120	8.06 69.5	0 0	3.45 884	7.55 102	2.80 72.5
0 0	0 0	1.06 29.0	8.00 180	3.46 145	0.04 4.80	0.41 77.3	0.22 29.6	0 0	0 0	0 0	0 0
0	0	0 0	0 0	0				0	0 0	0 0	0 0
0	0	0.15 75.0	0 0	0.10				0	0 *	0 0	0 0
0	0	0.91 27.9	8.00 240	3.37				0	0 0	0 0	0 0
0	0	0.30 88.2	1.43 ∞	0.69				0 *			
0	0 0	2.28[c] 393	13.42[c] 482	6.14[c]							

35	36	36	36	38	38	38	38	39	39	39
1934	1935	1936	Avg	1934	1935	1936	Avg	1935	1936	Avg
193	4534	5083	4839	202	151	151	168	527	357	442
	0	0	0					75	80	
	10	10	10	100	100	100	100	15	10	}100
100	90	90	90					10	10	
	4	4	4	4	4	4	4	24-12	24-12	24-12
	Y	Y	Y	Y	Y	Y	Y	Δ & Y	Δ & Y	Δ & Y
	240	240	240					200	200	200
	Trans	Trans	Trans	Line	Line	Line	Line	Trans	Trans	Trans
	20	20	20	15 to 100	15 to 100	15 to 100	15 to 100	10	10	10
30.0 53.5	10.0 510	18.40 3.36	14.41 3.28	0.97 19.1	0.66 20.6	2.65 70.8	1.39 39.8			
	0.63 185	0.96 122	0.81 168	0.33 31.1	0.66 220	0 0	0.40 99.0	0	0 0	0 0
						0		0	0	0
						0		0	0	0
						0		0	0	0
	0.54 1350	1.38 657	0.98 1090		0.66 412	0.66 254	0.66 314	0	0	0
	0.02 50	0.26 200	0.15 223	50.0[d]					0	0
	0.09 225	0.14 ∞	0.11 456						0	0

40	42	44	44	44	45	55	69	69	69
1935	1935	1935	1936	Avg	1936	1936	1935	1936	Avg
400	112	50	50	50	2580	447	122	136	129
							100	100	100
100		100	100	100	100	100			
4	4	11.5	11.0	11.0	6.9	23-69	4.8	4.8	4.8
Y	Y	Y	Y	Y	Y	Δ & Y	2Φ4W	2Φ4W	2Φ4W
		450	450	450					
Trans		Line	Line	Line	Line	Line	Trans.	Trans	Trans.
25		13	20-25			28			
3.00 126	3.57 89.0	10.0 93.4	10.0 450	10.0 257	6.20 70.1	4.92 34.4	13.9 ∞	2.94 35.3	8.15 220
0.50 87.7	0 0	0 0		0	0.43 53.1	0.22 17.3	0 *	0.74 ∞	0.39 ∞
	0 0	0 0		0			0 *	0.74 ∞	0.39 ∞
	0 0	0 0		0			0 *	0 *	0 *
	0 0	0 0		0			0 *	0 *	0 *
0.75 227		0 0		0	0.12 57.1		0.82 ∞	0 *	0.39 ∞
0 0		0 *		0	7.14 196	0.22 11.6	0.82 ∞		0.82 ∞
0 0		0 *		0			0 *		0 *

70	70	70	70	70	70	70	70
1936							Avg.
153	10	8	12	121	26	20	350
100	100			100			
		100			100		}100
			100			100	
2.3	13	13.2	2.3	2.4	12	13.8	
Δ	Y	Δ	Δ	Δ	Δ	Δ	
200	200	200	200				
Line	Line	Line	Line	Trans	Trans	Trans	
	15	15	15	6	5.5	6.5	
0.65 4.20				0 0	0 0	0 0	0.31 2.40
			16.67 750	0 0	0	0	1.12 50.5
			8.33	3.31 139			
				8.27			

c. Company estimate

d. As compared with surrounding area

Table V. Summary of Operating Data by Company and by Year

Gapped Interconnection With Tie to Case—Figure 5

Company	4														33			34
Year	1934				1935						1936			Avg.	1935	1936	Avg.	1936
No. of Installations Reported On	120	354	20	27	193	60	70	66	196	13	62	124	367	557	312	777	545	10[a]
Type of Territory by Percentages																		
Urban	45	90			6	0			2	0	100					4.6	3.30	100
Suburban	34	10			25	22			0	38		100		}100		0	0	
Rural	41	0	100	100	69	78	100	100	98	62			100		100	95.4	96.7	
Voltage of System - kv.	2.3	2.3	11&13.2	11&13.2	2.4	6.6	11	11	13	13	2.3-13.2	2.3-13.2	2.3-13.2		6.6	2.3-12		2.3
Phase Connection	Δ	Δ			Δ	Δ	Δ	Δ	Δ&Y	Δ	Δ	Δ	Δ		Δ	Δ&Y		Δ
Fusing Schedule - %											250	250	250					250
Position L.A. With Respect To Fuse					Both	Trans	Line	Trans.	Both	Line	Both	Both	Both		Both	Both		Line
Average Ground Resistance - Ohms	75	25	25	60	60	54	50	23	50	6	20	25	25	38		30		
Failure Data per 100 Installations																		
Primary Fuses Blown	0.83	2.26	20	111	4.15	1.67	14.3	30.3	75.0	15.4	37.1	35.5	44.6	27.6		8.11	8.11	10.0
Ratio - Change over Std. Connection - %					8.50	2.30	-15.9	33.8	83.5	17.2	1051	454	145	230		124	69.9	135
Transformer Winding	0.83	0	0	0	0	1.67	2.86	3.03	4.08	7.70	0	0	3.54	1.67	0.96	0.26	0.46	0
Ratio Change over Std Connection - %					0	10.8	16.6	17.6	23.7	44.7	0	0	135	128	114	49.0	61.3	0
Primary Only		0	0	0	0	1.67	2.86	1.52	3.57	0	0	0	2.45	1.29				0
Ratio Change over Std. Connection - %					0	43.3	82.9	44.0	103	0	0	0	256	182				0
Secondary Only		0	0	0	0	0	0	0	0.51	0	0	0	0.27	0.13				0
Ratio Change over Std. Connection - %					0	*	0	0	14.8	0	0	0	39.1	43.0				0
Primary & Secondary		0	0	0	0	0	0	1.52	0	7.70	0	0	0.82	0.32				0
Ratio Change over Std. Connection - %					0	0	0	14.8	0	74.6	0	0	85.5	53.7				0
Lightning Arrester	0		0		2.59	0	0	0	5.10	0	0	0	2.45	1.86				
Ratio Change over Std. Connection - %					33.3	0	*	*	∞	*	0	0	89.1	227				
Customers' Meters Burned Out	0	0	0	0	0	0	0	0	0	0	0	0	1.36	0.30				
Ratio Change over Std. Connection - %					0	*	*	*	*	*	0	0	11.5	12.8				
Customers' Wiring, Etc. Damaged	0	0	0	0	0	0		0	0	0	0	0	0	0				
Ratio Change over Std. Connection - %					0	*		*	*	*	0	0	0	0				
Tie to Case - Solid (S) or Gapped (G)	G	G	S	S	S	S	S	S	S	S	Both	Both	Both		G	S		G

* No Failures either connection.

a. Slight modification of Fig. 5.

Table VI. Summary of Operating Data by Company and by Year

Solid Interconnection Obtained by Common Primary and Secondary Neutral—Figure 6

Company	1	3			4						9			11			12				
Year	1935	1935	1936	Avg.	1935		1936			Avg.	1934	1935	Avg.	1934	1936	Avg.	1934	1936	Avg.	1935	
No. of Installations Reported On	10	52	5500	2771	7	7	29	42	572	329	3375	6364	4970	4709	757	2733	3175	2490	2833	1050	301
Type of Territory by Percentages																					
Urban			100			100	100				100	}100	}100	100	100	100	}100	100	}100	10	100
Suburban								100		}100										40	
Rural	100	70-90			100				100											50	
Voltage of System - kv.	2.4	13	4&12.5		2.4	4	4, 11, and 13.2				4	4	4	4	4	4	4	4	4	4	4
Phase Connection		Y	Y				Y				Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Fusing Schedule - %	240						250	250	250		240	240	240								
Position L.A. With Respect To Fuse	Line	Line	Trans.		Trans.	Trans.	Trans.	Trans.	Trans.	Trans.		Both	Both	Line	Line	Line	Line	Line	Line	Line	Line
Average Ground Resistance - Ohms	2				18	3	3	3	3	30	10	50	35	0.6	0+		1.0	0+	0-1		20-
Failure Data per 100 Installations																					
Primary Fuses Blown	0	7.69	2.95	2.99	0	0	0	11.9	8.92	8.53	6.10	0	2.20	0.06	1.32	0.24	0.72	0.40	0.58	0.76	1.33
Ratio - Change over Std Connection - %	0	44.4	46.0	54.9	0	0	0	152.0	28.9	70.9	22.2		5.15	†	†	†	†	†	†	47.5	229
Transformer Winding	0	0	0.58	0.58	0	0	0	0	1.57	1.37	0.78	0.19	0.40	0.04	0.40	0.09	0.22	0.36	0.28	0	0
Ratio Change over Std Connection - %	0	0	45.4	55.4	0	0	0	0	60.1	104	26.2	11.2	13.4	†	†	†	†	†	†	0	0
Primary Only	0	0			0	0	0	0	0.35	0.30					0.40			0.20		0	0
Ratio Change over Std Connection - %	0	0			0	0	0	0	36.5	42.2					†			†		0	0
Secondary Only	0	0			0	0	0	0	0.35	0.31					0					0	0
Ratio Change over Std. Connection - %	0	0			0	0	0	0	50.7	102					†					0	*
Primary & Secondary	0	0			0	0	0	0	0.87	0.76					0					0	0
Ratio Change over Std. Connection - %	*	0			0	0	0	0	90.6	127					†					0	*
Lightning Arrester					0	0	0	0	0.87	0.76		0.49	0.49	0.02	0.53	0.09	0.22	0.24	0.23	0	0
Ratio Change over Std. Connection - %					0	0	0	0	31.6	92.9		12.8	10.7	†	†	†	†	†	†	0	0
Customers' Meters Burned Out	0				0	0	0	0	0.17	0.15				0.02	4.10	0.59	0.22	1.65	0.85		
Ratio Change over Std. Connection - %	0				0	0	0	0	1.44	6.49				†	†	†	†	†	†		
Customers' Wiring, Etc. Damaged	0				0	0	0	0	0	0				0	0	0	0	0.04	0.02		
Ratio Change over Std Connection - %	*				0	0	0	0	0	0				†	†	†	†	†	†		
Grounded Tanks	No	No	Yes		No	No	Yes	Yes	Yes			No			Some			Yes		No	No

* No failures either connection.

† Standard Connection not used.

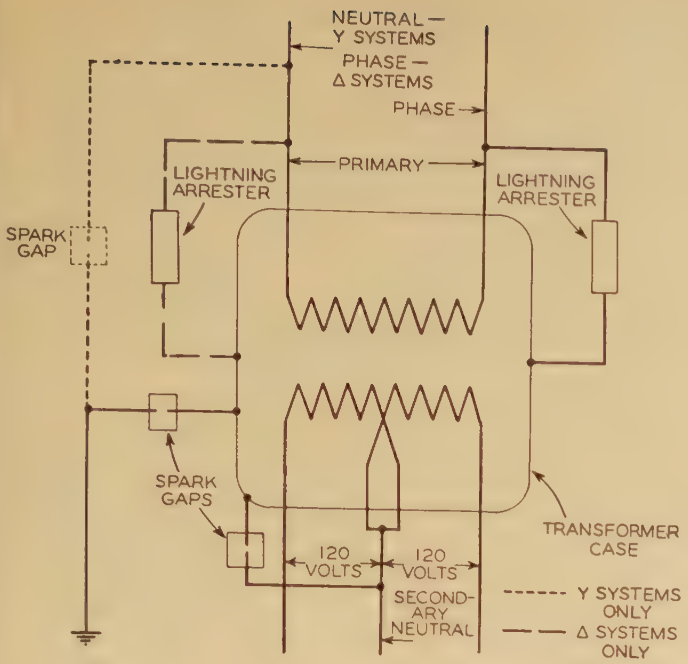


Figure 8 (left). Three-point protection

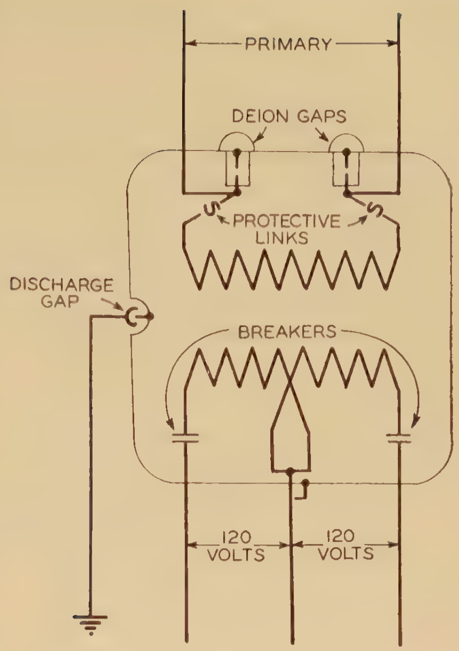


Figure 9 (right). Type CSP transformer

the data indicates some benefit of the tie with the tank. The common primary and secondary neutral seem to be about equally effective as the conventional interconnection. In rural areas the *SP* transformer ranks next to the solid interconnection schemes. In general it is believed that three-point protection ranks next. The gapped interconnection and the standard connection rank last. The gapped interconnection seems no better if as good as the standard connection. A possible explanation is that the impulse flashover of the gaps used may be as high as the bushing flashover voltages. If the secondary bushings flashover on a transformer protected

Table VI (Continued). Summary of Operating Data by Company and by Year

Solid Interconnection Obtained by Common Primary and Secondary Neutral—Figure 6

	15			18			20	21				28					31	32					33	50				51			56	70		
AVG.	1935	1936	AVG.	1935	1936	AVG	1935	1935	1936		AVG	1934	1935	1936		AVG	1936	1935	1936			AVG.	1936		1936		AVG.	1935		AVG	1936	1936		AVG.
1624	10000	10000	10000	793	1539	1166	2020	4600	4835	3[a]	4719	434	453	444[a]	111[b]	481	2847	7250	5120	1578	1182	7565	494	2[c]	80[c]	503[c]	585	2078	3638	5716	2830	210	53	263
				100			100	85	100					100			98.0	70	100				12.4	100				100		36.3	100	100		79.8
100	100	100	100		100	100		15			100	100	100		100	100		20		100		100	0		100		100			0				
								0		100								10			100		876			100			100	63.7			100	20.2
4	4	4	4	4	4	4	2.4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2.3-12	12	12	12	12	4	12		4	4	4	4
Y	Y	Y	Y	Y	Y	Y	Δ	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Δ&Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y
								240	240	240	240							240	240	240	240	240						240	240	240		240	240	240
LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE	LINE						TRANS	TRANS	TRANS	LINE	LINE	LINE	LINE
20-				3	0.5-			21	02±1			10	10	10	10	10		10	0.7	10	15	10	30	17	17	17	17		20	20	0+			
1.23 80.3	1.78 64.7	3.00 41.2	2.39 33.8	1.01 †	0.52 62.7	0.69 59.7	1.14 740	0.41 9.0	0.41 †	0 †	0.41 10.1	0.23 †	0 *	0 0	0 0	0.07 1.74	0.84 ∞	0.32 †	0.10 †	0.25 †	0.42 †	0.24 †	3.04 46.4	100	6.25	2.78	3.59 41.5	2.89 †	9.12 †	6.85 †	0 †	0.95 6.14	3.77 35.5	1.52 11.7
0.03 14.5	0.98 ∞	1.17	1.08	0.25 †	0.33 540	0.30 42.3	0.05 200	0.07 15	0.02 †	0 †	0.04 6.17		0 *	0 0	0 0	0 0	0.46 128	0.14 †	0.04 †	0.13 †	0.17 †	0.11 †	0.41 77.3	0 0	0 0	0.40 977	0.34 29.6	0.05 †	0.27 †	0.19 †	0 †			
0 0				0.25 †	0.33 660	0.30 187		0.04 ∞	0.02 †	0 †	0.03 ∞		0 *	0 0	0 0	0		0.04 †	0.02 †	0 †	0.08 †	0.03 †		0 0	0 0	0.20 125	0.17 272	0.05 †	0.14 †	0.11 †	0 †			
0 0				0 †	0 0	0 0		0.02 ∞	0 †	0 †	0.01 ∞		0 *	0 *	0 0	0		0 †	0 †	0 †	0 †	0 †		0 *	0 *	0 *	0 0	0 †	0 †	0 †	0 †			
0.03 320				0 †	0 0	0 0		0 0	0 †	0 †	0 0		0 *	0 0	0 0	0		0.10 †	0.02 †	0.13 †	0.08 †	0.07 †		0 0	0 0	0.20 800	0.17 54.5	0 †	0.14 †	0.09 †	0 †			
0.09 47.2	0 *	0.06 ∞	0.03 10.7					0.04 ∞	0.04 †	0 †	0.04 125	0.46 †	0 *	0.45 300	0 0	0.28		0.70 †	0.33 †	0.95 †	1.89 †	0.69 †						0.24 †	0.41 †	0.35 †	0 †			
								0 *	0.02 †	0 †	0.11 ∞	1.62 †						0.29 †						0 *	0 *	0 *	0 *	0 †	0.16 †	0.11 †	0 †			
								0 *	0 †	0 †	0 *	0 †						0.33 †										0 †	0 †	0 †	0 †			
No	No	No	No	No	Some		No	No	Yes	Yes			Some	Yes	Yes		No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No	No	No

a. Rural type transformers using spill gap b Includes Fig. 3 c. Horn gap instead of L.A.

Table VII. Summary of Operating Data by Company and by Year

Surge-Proof Transformer—Figure 7

Company	1			3	4									7			
Year	1934	1935	Avg	1936	1935					1936			Avg	1934	1935	1936	Avg.
No. of Installations Reported On	60	150	105	32	27	255	16	1	4	120	56	418	449	551	672	672	632
Type of Territory by Percentages																	
Urban				100	13	31	12			100			100		10		100
Suburban					0	18	50				100			100			
Rural	100	100	100		87	51	38	100	100			100			90		
Voltage of System - KV.	4&12.5	4&12.5	4&12.5	4&13.2	2.4	2.4	4	7.6	13	2.3-132	2.3-132	2.3-132			2.4&4	4	
Phase Connection	Y	Y	Y	Y	Δ	Δ	Y	Δ	Δ	Δ&Y	Δ&Y	Δ&Y		✓	Y	Y	
Fusing Schedule - %										250	250	250					
Average Ground Resistance - Ohms	20	15	16.4		83	120	3	150	150	50	75	100		95.6	150		
Failure Data Per 100 Installations																	
Primary Fuses Blown	0	0.67	0.49	375	3.70	3.14	0	0	25.0	5.83	46.5	9.80	9.36	9.78	11.0	15.92	18.10
Ratio-Change over Std. Connection-%	0	17	5.65	688	7.60	6.42	0	0	27.9	165	594	31.7	77.9	91.9	82.7	93.0	106
Transformer Winding	0	0	0	0	3.70	0	0	0	0	0.83	0	0.48	0.45	0.18	0.30	0	0.32
Ratio Change over Std. Connection-%	0	0	0		59.5	0	0	0	0	154	0	18.4	340	35.4	57.7	0	41.2
Primary Only	0	0	0	0	3.70	0	0	0	0	0	0	0	0.11		0.15	0	0.07
Ratio Change over Std. Connection· %		0			111	0	0	0	0	0	0	0	15.6		150		
Secondary Only	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
Ratio Change over Std. Connection-%		0			0	0	0	*	0	0	0	0	0		0		
Primary & Secondary	0	0	0	0	0	0	0	0	0	0.83	0	0.48	0.33		0.15	0	0.30
Ratio Change over Std. Connection - %		*			0	0	0	0	0	615	0	50.0	56.6		93.7		
Deion Gap	0	0	0	0	0	0.78	0	0	0	0	0	0.72	0.56	1.99	1.48	3.28	2.96
Ratio Change over Std. Connection - %	0	0	0		0	10.0	0	0	*	0	0	26.2	68.0	60.2	36.2	111	102
Customers' Meters Burned Out	0	0	0		0	0	0	0	0	0	1.79	0	0.11				
Ratio Change over Std. Connection-%	0	0	0		0	0	0	*	*	0	271	.0	4.70				
Customers' Wiring, Etc. Damaged	0	0	0		0	0	0	0	0	0.83	0	0	0.11		0.15	0.30	0.22
Ratio Change over Std. Connection-%	*	*			0	0	0	*	*	177	0	0	27.1		107	∞	167
Cover Removal After Fuse Failure To Inspect Gaps	No	Yes			Yes	Some	No		No	50%	50%	50%		Yes	Yes	Yes	Yes

Company	23				24			25	29	33				34			
Year	1934	1935	1936	Avg.	1934	1936	Avg.	1934	1934	1934	1935	1936	Avg	1934	1935	1936	Avg.
No. of Installations Reported On	5	5	5	5	5	528	267	8	18	96	138	141	125	14	11	11	12
Type of Territory by Percentages																	
Urban		0	60	100		97	100	100			14	13.5	10.1	100	100	100	100
Suburban	100	60	0						100		0	0	0				
Rural		40	40		100	3				100	86	86.5	89.9				
Voltages of System- KV.		2.4&4	2.3&4			2.3&6.9				2.4-66	2.4-6.6	2.3-12		2.4	2.4	2.4	2.4
Phase Connection		1φ&Y	Δ&Y			1φ&Δ				Δ&Y	Δ&Y	Δ&Y		Δ	Δ	Δ	Δ
Fusing Schedule - %	200	200	200	200		240								240	240	240	240
Average Ground Resistance - Ohms	20				20	25	25	12				30					
Failure Data Per 100 Installations																	
Primary Fuses Blown	20	0	0	6.67		2.27	2.27		0	2.09	0	7.10	3.12	0	9.09	9.09	5.55
Ratio Change over Std. Connection· %	1739	0	0	368		121	157		0	15.4	0	108	26.8	0	2330	123	144
Transformer Winding	0	0	0	0	0	2.08	2.06	0	0	0	0	0.71	0.27	0	0	9.09	2.78
Ratio Change over Std. Connection - %	*	0	*	0	†	195	211		0	0	0	134	41.0	0	0	1750	602
Primary Only	0	0	0	0	0					0	0		0	0	0	0	0
Ratio Change over Std. Connection - %	*	0	*		†										0	0	0
Secondary Only	0	0	0	0	0					0	0		0	0	0	0	0
Ratio Change over Std. Connection·%	*	0	*		†										*	0	0
Primary & Secondary	0	0	0	0	0					0	0		0	0	0	9.09	2.78
Ratio Change over Std. Connection %	*	0	*		†										0	2270	1080
Deion Gap	0	0	0	0	0			0	0	0				0	0	9.09	2.78
Ratio Change over Std. Connection %	0	0		0	†				0					*	0		18550
Customers' Meters Burned Out	0	0	0	0	0	0	0	0	0	0							
Ratio Change over Std. Connection-%	*	0		0	†				0								
Customers' Wiring, Etc. Damaged	0	0	0	0	0	0	0	0	0	0							
Ratio Change over Std. Connection-%	*	*		*	†				0								
Cover Removal After Fuse Failure To Inspect Gaps	Yes	Yes	Yes	Yes	No	Yes		No	No	No	No	No	No	No	No	No	No

Table VII (Continued). Summary of Operating Data by Company and by Year

Surge-Proof Transformer—Figure 7

9[a]						14				15			
1934	1936				Avg.	1934	1935	1936	Avg.	1934	1935	1936	Avg.
99	554	230	511	96	745	11	11	16[b]	13	591	1051	1262	968
	70 30 0	0 20 80	10 20 70	10 20 70	100	100	100	100	100	100	100	5 95	
	2.3 Δ 230	3.8&8 Δ&Y 230	6.9&11.5 Δ&Y 230	11.5&13.8 Δ 230	230	4.8 Δ 300	4.8 Δ 300	4.8 Δ 300	4.8 Δ 300	4 Y	4 Y	4 Y	4 Y
200						66.5	72	64	68				
1.01 2.00	0	0	0	0	0.07 0.16	9.10 46.4	27.3 195	31.2 97.5	23.7 108	0.34 4.45		2.30 31.6	1.62 22.9
0 0	0		0.39	2.08	0.32 10.5	0 0	0 ★	0 ★	0 0	1.01 29.2	0.38 ∞	0.40	0.52
0	0					0	0 ★	0 ★	0		0 ★	0	0
0	0					0	0 ★	0 ★	0		0.19 ∞	0.08	0.13
0	0					0	0 ★	0 ★	0		0.19 ∞	0.32	0.26
16.16	0.18 2.86	1.30			2.29 49.8	0	0 0	0 ★	0	3.05 925	0.38 ∞	0.47 ∞	0.97 345
0						0	0 0	0 ★	0				
0						0	0 ★	0 ★	0				
Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No		No	No	No	No

16	17				19				21			22		
1934	1934	1935	1936	Avg.	1934	1935	1936	Avg	1935	1936	Avg	1934	1936	Avg.
30	12	15	16	14	29	30	30	30	3	3	3	50	45	48
	100	100	100	100	100	100	100	100	100	100	100	100	33.3 11.1 55.6	100
	12 Y 200	12 Y 200	12 Y 200	12 Y 200		2.4 Δ	2.3-6.9 Δ		4 Y 240	4 Y 240	4 Y 240		6.9 Δ 240	
25	10.5	15			43							10	7	8.5
0	16.67 487	13.30 161	12.50 258	13.95 551	13.70 156	13.30 243	6.67 62.0	11.25 168	0 0	0 †	0 0	0	20.0 97.0	9.48 56.9
0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 †	0 0	0 0	0 0	0 0
0	0	0 0	0 ★	0	0	0	0	0	0 ★	0 †	0 ★	0	0 0	0
0	0	0 0	0 ★	0	0	0	0	0	0 ★	0 †	0 ★	0	0 ★	0
0	0	0 0	0 0	0	0	0	0	0	0 0	0 †	0 0	0	0 0	0
	16.67 4900	0 0	0 0	4.65 1191	3.46 392	0 0	0 0	1.13 314	0 ★	0 †	0 0	0	0	0
0 ★	0 0		0 ★	0 0	0 ★	0 ★		0 0	0 ★	0 †	0 ★			
	0 0		0	0 0	0 0	0 ★		0 0	0 ★	0 †	0 ★	0 0		
	Yes	Yes	No		No	No	No	No		Yes		No	No	No

36				42	50							55	70		
1934	1935	1936	Avg.	1935	1935		1936				Avg	1936	1936		Avg.
71	140	140	117	76	79	18	4	4	9	64	89	8	10	13	23
100	100	100	100		100	33 67	100	100	100	100	100			100	
	4 Y 240	4 Y 240		4-12 Y	2.4 Y	6.6 Y	12 Y 240	12 Y 240	12 Y 240	4 Y 240		6.9 Δ	12 Y 200	6.9 Δ	
2.0	25	0.2	10.4		17	17						28		15	
0 0	0 0	0 0	0 0	18.4 459	0 0	0 0	25.0	25.0	0	9.38 308	4.50 52.0	0 0	10.00 64.5	0 0	4.35 33.4
0	0 0	0 0	0 0	0 0	1.27 80.9	0 0	0 0	0 0	0 0	0 0	0.56 55.5	0 0	0	0	0
0	0	0	0	0 0	1.27 116	0 0	0 0	0 0	0 0	0 0	0.56 89.3	0	0	0	0
0	0	0	0	0 0	0 0	0 ★	0 0	0 0	0 0	0 0	0 0	0	0	0	0
0	0	0	0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0	0	0	0
0	0 0	0 0	0 0		0 0	0 0				0	0	0	0	0	0 0
0	0 0	0 0	0 0		0 ★	0 ★				0 ★	0 ★	0 0	0	0	0 0
0	0 0	0 ★	0 0		0 ★	0 ★				0	0 ★	0	0	0	0
	Yes			Yes			No	No	No	No	No	No	No	No	No

★ No failures either connection.
† Standard Connection not used.
a. Includes Type C.S.P. Transformers.
b. Data on units subject to most lightning surges.

Table VIII. Summary of Operating Data by Company and by Year

Three-Point Protection—Figure 8

Company	4					7						18				22	24	25	33				42	50		
Year	1935	1936			Avg	1934		1935	1936		Avg	1934	1935	1936	Avg	1934	1936	1934	1934	1935	1936	Avg	1935	1935	1936	Avg
No. of Installations Reported On	723	234	58	130	573	62	50	110	60	50	111	20	19	19	19	100	350	20	22	69	19	33	14	213	314	264
Type of Territory by Percentages																										
Urban	47	100															100							100	100	100
Suburban	20		100		100								100	100	100	100		100								
Rural	33			100		100	100	100	100	100	100	100							100	100	100	100				
Voltage of System - KV	2.4	2.3&13.2	2.3&13.2	2.3&13.2	2.3&13.2	4	4	4	4	4	4	13.2	13.2	13.2	13.2		2.3&4.8			6.6	6.9&12		4&12	4	4	4
Phase Connection	Δ	Δ	Δ	Δ	Δ	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		14.Δ&Y			Δ	Δ&Y		Y	Y	Y	Y
Fusing Schedule - %		250	250	250													200									
Position L A With Respect To Fuse	Both	Both	Both	Both	Both	Line	Line	Line	Line	Line	Line	Line	Line	Line	Line		Line		Both	Both	Both	Both				
Average Ground Resistance - Ohms	175	7	10	20		80	21	70				3	3	3	3	10		12			36			17		
Failure Data Per 100 Installations																										
Primary Fuses Blown	3.60	1.28	20.7	1.54	3.76	11.30	6.00	15.50	16.67	28.0	15.35	5	5.27	15.80	8.62				0	0	0	0	0		1.27	1.27
Ratio - Change over Std. Connection - %	7.40	36.2	264	4.98	30.1	106	56.3	137	97.4	164	158	†	†	34.2	750				0	0	0	0	0		41.6	14.7
Transformer Winding	0.97	0.43	3.45	1.54	1.05	0	0	0	0	0	0	5	0	0	1.73	0		0	0	0	0	0		0	0	0
Ratio Change over Std Connection - %	15.6	79.6	363	59.0	80.1	0	0	0	0	0	0	†	†	0	243	0			0	0	0	0		0	0	0
Primary Only	0.69	0.43	0	0.77	0.61	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0		0	0	0
Ratio Change over Std Connection - %	20.7	127	0	80.2	86.2			0					†	0	0					0				0	0	0
Secondary Only	0.14	0	1.72	0	0.17	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0		0	0	0
Ratio Change over Std Connection - %	11.7	0	1452	0	57.9			0					†	*	0					0				0	0	0
Primary & Secondary	0.14	0	1.72	0.77	0.26	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0		0	0	0
Ratio Change over Std Connection - %	7.30	0	358	80.2	43.6			0					†	*	0					0				0	0	0
Lightning Arrester	1.25	0.43	6.90	0	1.22	12.8	6.00	19.10	8.33	20.0	14.15	0						0	0		0					
Ratio Change over Std Connection - %	16.1	159	1046	0	149	388	182	465	282	677	490	†														
Customers' Meters Burned Out	0	0.43	0	0	0.09				0	0		0						0	0		0			0	0	0
Ratio Change over Std. Connection - %	0	35.6	0	0	3.72							†												*	*	*
Customers' Wiring, Etc. Damaged	0	1.71	0	0.77	0.35			0.91				0				0		0	0		0			0		
Ratio Change over Std. Connection - %	0	3.64	0	160	85.4			650				†												*		

* No failures either connection
† Standard Connection not used

by the standard connection, the effect is similar to the action of a gapped interconnection on three-point connection. This may explain why the three-point connection, the gapped interconnection, and the standard connection show similar operating results. It is also interesting to note that the relative performance of the various schemes of protection do not align in their expected relative order of merit when data on urban and suburban installations are compared. Of the 19 companies reporting data on type *CSP* transformers three state that they install primary fuses with them. Of 11 companies reporting data on type *CSP* transformers only one states that an increase in branch fuses blown was noted.

Table IX. Summary of Operating Data by Company and by Year

Type CSP Transformer—Figure 9

Company	1	3	4												5	6[b]				7			15			16	
Year	1935	1936	1934	1935							1936			Avg	1934	1935	1936		Avg.	1935	1936	Avg	1935	1936	Avg	1935	1936
No. of Installations Reported On	25	41	176	11	135	18	5	24	11	34	56	31	188	236	34[a]	17	26	1	22	361	598	480	350	421	386	262	753
Type of Territory by Percentages																											
Urban		100		10	23	17			14	3	100									25						30	20
Suburban			100	0	26	28			21	9		100		100		94	100		100				100	100	100	40	30
Rural	100			90	51	55	100	100	65	88			100		100	6		100		75						30	50
Voltage of System - KV	2.4&7.2	4&13.2		2.4	2.4	4	6.6		11	13	2.4-13.2	2.4-13.2	2.4-13.2			4	4	4	4	2.4&4	4	2.4&4	4	4	4	4.8-6.6	2.3-6.9
Phase Connection	Y	Y		Δ	Δ	Y	Δ	Δ	Δ	Δ&Y	Δ&Y	Δ&Y	Δ&Y			Y	Y	Y	Y	Δ&Y	Y	Δ&Y	Y	Y	Y	Δ	Δ&Y
Average Ground Resistance - Ohms	8		125		65	5		250	35	25	4	20	50		5	250	250	250	250							20	
Failure Data Per 100 Installations																											
Primary Fuses Blown	0	0	4.55	0	0	0	0	0	9.09	0	0	0	0.53	1.41	0	0	0	0	0	0	0	0		0	0		
Ratio Change over Std Connection - %	0	0	49.7	0	0	0	0	0	10.1	0	0	0	1.72	10.7		0	0	0	0	0	0	0		0	0		
Transformer Winding	0	0	0	0	0	5.55	0	0	9.09	0	0	0	0	0.28	0	0	0	0	0	0	0	0	0	0.71	0.39	0.76	0.93
Ratio Change over Std Connection - %	0	0	0	0	0	89.2	0	0	52.8	0	0	0	0	21.6		0	0	*	0	0	0	0	*			56.2	93.0
Primary Only	0	0	0	0	0	5.55	0	0	0	0	0	0	0	0.141	0	0	0	0	0	0	0	0	0	0	0	0	
Ratio Change over Std Connection %	0				0	167	0	0	0	0	0	0	0	19.9		*	*	*	*	0			*			0	
Secondary Only	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24	0.13	0	
Ratio Change over Std Connection %	0				0	0	*	0	0	0	0	0	0	0		*	0	*	0	0			*			0	
Primary & Secondary	0	0	0	0	0	0	0	0	9.09	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0.47	0.26	0.76	
Ratio Change over Std. Connection %	*				0	0	0	0	88.2	0	0	0	0	23.5		0	0	*	0	0			*				
Deion Gap	0	0	0	0	0	5.55	0	0	9.09	0	0	0	0	0.28		0	0	0	0	0	0	0	0	0	0	0	
Ratio Change over Std. Connection %	0		0	0	0	71.4	0	*	∞	*	0	0	0	34.4		*	*	*	*	0	0	0	*	*	0	0	
Customers' Meters Burned Out	0		1.14		0	0	0	0	0	0	0	0	0.53	0.42	0	0				0							0
Ratio Change over Std Connection %	0		1036		0	0	*	*	*	*	0	0	4.49	18.07		0				0							*
Customers' Wiring, Etc. Damaged	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.85	0	2.27	0.28	0.17	0.21					0
Ratio Change over Std. Connection %	*		0	0	0	0	*	*	*	*	0	0	0	0		*	1480		2235	200	54.8	156					*
Increase In Tap or Branch Fuses Blown	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No							

* No failures either connection
† Standard Connection not used.

a. Includes approx 10 Surge-Proof Transf's.
b. Not directly comparable with Fig 1.
c. Transf's equipped with one bushing and one

In comparing the relative merit of the various schemes of protection in reducing *transformer winding failures* a study of tables X to XV indicates conflicting trends which make it difficult to draw definite conclusions. If rural installations only are considered the *CSP* transformer shows the best performance with the common primary and secondary neutral system next with the *SP* transformers, the three-point connection, the standard connection, the gapped interconnection, and the solid interconnection following in the order listed. However, when urban and suburban installations are considered almost the reverse trend is noted in that the various types of solid interconnection show the best performance with the *CSP* transformer, the *SP* transformer, the three-point connection, the gapped interconnection, and the standard connection following in that order. This lack of consistency may be due to the fact that in all cases the rate of transformer-winding failures is so small that there is less probability of distinct trends being established without collecting data over a number of years. Moreover the age and design of the transformer, the number of lightning surges to which it has been previously exposed, the degree of exposure, and isokeraunic level all affect the probability of transformer failure. The fact that *SP* and *CSP* transformers are both relatively new and of more modern design is undoubtedly at least in part a contributing factor in their good performance as well as the protection scheme used on them. It is interesting to note that in both methods of comparison that the three-point connection, the standard connection, and the gapped interconnection are all grouped together possibly for the same reason that was discussed under rates of primary fuses blown. In comparing the performance of rural installations it is difficult to explain the difference in the performance of the common neutral system and the solid interconnection as they are essentially the same in so far as lightning protection is concerned. It is believed that it is safe to conclude that the newer schemes are better than the standard connection but with little to choose between the three-point connection, the gapped interconnection, and the standard connection.

In considering the effect of the various methods of protection on the *rate of arrester failures* the data are somewhat conflicting but show that the *CSP* transformer and the several methods of solid interconnection have the lowest failure rates. The three-point connection consistently shows the maximum failure rate. However, this may be due to the small number of installations and the fact that most of them were protected by a type of arrester with a known high failure rate. Since the type of arrester has a considerable bearing upon the failure rate, definite conclusions cannot be drawn relative to the effect of the type of protection scheme used. However, since the failure rates for solid interconnections are not higher than those for the standard connection, it can be concluded that the fear that has been expressed that with solid interconnection a heavier duty may be placed on the arrester causing more failures is without foundation. Since in case of type *SP* transformers a deion-gap failure cannot be noted unless the top of the transformer tank is removed and an examination made, the practice of the companies as to this point was determined. Of 17 companies reporting this point on type *SP* transformers, seven reported that the tank covers are removed after primary fuses are blown. Unless this is done gap failures may not be observed.

Table IX (Continued). Summary of Operating Data by Company and by Year

Type CSP Transformer—Figure 9

17				18				21			22			33			34	36	38			40	42	44	45	50			55	66			69			70		
1935	1936		Avg	1935	1936		Avg.	1935	1936	Avg	1935	1936	Avg	1935	1936	Avg	1935	1935	1935	1936	Avg.	1935	1935	1935	1936	1935	1936	Avg.	1936	1935	1936	Avg	1935	1936	Avg.	1936		Avg.
4	4	4	6	14	44	7	33	4	4	4	133	98	115	145	654	400	3	5	39	39	39	83	3	10	1338	74	132	103	43	50	50	50	1	1	1	8	38	46
100	100		66.7	100				100	100	100	0	29.6			1.8	1.5	100					59			20	42	22.8									97.5		
					100	100	100				40	153	100		0			100	100	100	100	17			0	0	24.2	100					100	100	100	0		100
		100	33.3								60	55.1		100	98.2	98.5						24		100	80	58	53.0		100							62.5	100	
4	4	12	4&12	4	4	13.2		4	4	4	6.6	6.9	6.9	2.4-6.6	2.3-12	2.3-12	2.4	4	2.4	2.4	2.4	4	4-12	4	2.3&6.9	6.6	12	6.6&12	6.9	2.3-13	4-13.8	2.3-13.8	4.8	4.8	4.8	2.3&12	6.9	
Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Δ	Δ	Δ	Δ&Y	Δ&Y	Δ&Y	Δ	Y	Δ	Δ	Δ	Y	Y	Y	Δ	Y	Y	Y	Δ	Y	Δ&Y	Δ&Y	2&4W	2&4W	2&4W	Δ&Y	Δ	
13				3	3	3	3	1.5			15				30			25		15-200		2		13		17			28	10	10	10				15		
0	0	0	0	0	0	14.3	1.54	0	0	0		0		0	0.76	0.63	0	0	0	0	0	0	0	0	0				0	0			0	0	0		0	0
0	0	0	0	†	0	31.0	134	0	†	0		0		0	11.6	5.38	0	0	0	0	0	0	0	0	0				0	†			*	0	0		0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0		0	0
0	0	0	0	†	0	0	0	0	†	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.65	0	0	0	0	†	†	†	*	*	*			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
0	0	*		†	0	0	0	*	†	*	0	0		0			0	0	0	0		0	0	0		0	0	0		†	†	†	*	*	*			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
0	0	*		†	0	*	0	*	†	*	0	*		0			*	0	0	0		0	0	0		*	*	0		†	†	†	*	*	*			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0		0	0
0	0	0		†	0	*	0	0	†	0	0	0		0			0	0	0	0		0	0	0		0	0	0		†	†	†	*	*	*			
25				0	0	0	0	0	0	0	0	0	0		0.46	0.46	0	0	0	0	0	0		0	0.07	0	0	0	0	0	0	0	0	0	0		0	0
14,700				†				*	†	0	0						0	0	0	0	0	0		0	33.3	0				†	†	†	*	*	*			
	0	0	0					0	0	0								0		0		0		0		0	0	0	0	0	0	0	0				0	0
	0	*	0					*	†	*								0		0		0		*		*	*	*	0	†	†	†	*				0	0
	0	0	0					0	0	0								0		0		0		0		0				0	0	0	0				0	0
			0					*	†	*								0		0		0		*		*				†	†	†	*					
	No	No	No								No				No					No		No		No		No	No	No	d	No	No	No	No	No	No	e	No	

d. Decrease noted. e. Increase noted on urban installations

Table X. Combined Operating Data on Various Methods of Protecting Distribution Transformers From Lightning for 1934, 1935, and 1936

All Types of Territory

Type of Protection	Average Number Installations	Average Ground Resistance	Failures per 100 Installations				
						Customers'	
			Primary Fuses Blown	Transformer Winding Failures	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	159,138	60.0	6.35	0.717	1.17	1.10	0.103
Solid interconnection**	146,738	13.2	1.85	0.350	0.551	1.01	0.079
Gapped interconnection	11,029	48.8	10.10	0.676	0.963	1.97	0.141
Three-point protection	769	34.8	5.22	0.590	3.92	0.054	0.364
Surge-proof transformer	3,164	58.2	5.38	0.43	1.21*	0.036	0.102

* Deion gaps damaged per 100 installations. ** Includes common-neutral type.

Table XI. Combined Operating Data on Rural Installations for Various Methods of Protecting Distribution Transformers From Lightning for 1934, 1935, and 1936

Type of Protection	Average Number Installations	Average Ground Resistance	Failures per 100 Installations				
						Customers'	
			Primary Fuses Blown	Transformer Winding Failures	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	15,645	93.0	9.98	0.565	2.24	1.205	0.132
Solid interconnection*	5,738	19.1	6.26	1.04	0.680	0.352	0.137
Gapped interconnection	9,020	45.3	10.95	0.730	0.965	2.04	0.080
Three-point protection	217	42.7	8.28	0.460	8.06	0	0.554
Surge-proof transformers	890	85.5	7.72	0.272	1.66**	0	0.056

* Includes common primary and secondary neutral. ** Deion gap failures.

Table XII. Combined Operating Data Upon Various Methods of Protecting Distribution Transformers From Lightning for 1934, 1935, and 1936

Urban and Suburban Installations

Type of Protection	Average Number Installations	Average Ground Resistance (Ohms)	Failures per 100 Installations				
						Customers'	
			Primary Fuses Blown	Transformer Winding Failures	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	84,991	77.7	3.65	0.660	0.593	0.736	0.066
Solid interconnection*	80,235	9.1	0.989	0.204	0.192	1.45	0.099
Gapped interconnection	1,270	56.7	6.62	0.455	0.451	1.16	1.19
Three-point protection			No urban or suburban installations in 1934				
Surge-proof transformers	221	33.4	9.25	0.453	0.153	0.167	0.168

* Includes common primary and secondary neutral. ** Deion gap failures per 100 installations.

While the data for *meters burned out* and *troubles on customers' premises* are not conclusive, it can be concluded that solid interconnection does not increase the probability of trouble on the customers' premises due to lightning.

Effect of Ground Resistance

Since the resistance of lightning-arrester grounds is believed to have a material effect upon the degree of protection rendered, the data have been analyzed to determine such effects in tables XVI and XVII. In the analyses it will be noted while no consistent trend is evident that in general the trend of primary fuses blown and transformer-winding failures are upward as the ground resistance increases. When it is considered that the data are analyzed by the average ground resistance of each company reporting and that this average ground resistance is estimated, it is evident that these two tables cannot be considered entirely conclusive. However, it is believed that they are indicative of general trends.

Table XVI in most cases, except for the three-point connection, has sufficient number of installations in each range of ground resistances. However, this table includes all types of territory. When the data for rural installations only is segregated as in table XVII, too few installations exist in many ranges of ground resistances to give usable averages. In table XVII it should be noted that the rate of primary fuses blown and transformer winding failures for ground resistances up to 30 ohms are slightly higher for interconnection than for the standard connection. This may be due in part to the inclusion of gapped interconnection in the classification

Table XIII. Combined Operating Data on Various Methods of Protecting Distribution Transformers From Lightning for 1935 and 1936

All Types of Territory

Type of Protection	Average Number Installations	Average Ground Resistance	Failures per 100 Installations									
			Primary Fuses Blown			Transformer Windings Damaged					Customers'	
			Total	Lightning Arrester on Line Side of Fuse	Lightning Arrester on Transformer Side of Fuse	Total	Primary Only	Secondary Only	Primary and Secondary	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	153,698	59.0	5.08	4.55	6.29	0.655	0.214	0.081	0.317	0.878	1.04	0.100
Solid interconnection	123,102	10.7	1.36	1.01	2.12	0.333	0.068	0.030	0.130	0.455	1.37	0.092
Solid interconnection with tie to case	2,715	27.9	1.80	1.40	N.D.	0.276	0.096	0.096	0.145	0.049	0	0
Gapped interconnection	14,627	56.1	9.20	5.23	12.40	0.634	0.254	0.053	0.561	0.875	2.12	0.156
Gapped interconnection with tie to case	1,125	36.9	24.90	13.99	16.67	1.42	1.72	0.172	0.432	2.08	0.435	0
Common primary and secondary neutral	40,734	10.1	1.74	1.10	5.15	0.413	0.063	0.007	0.053	0.300	0.343	0.085
Surge proof transformer	3,850	48.1	5.81			0.442	0.048	0.048	0.178	0.840*	0.046	0.115
Three-point protection	1,016	44.0	5.05	17.45	N.D.	0.595	0.347	0.099	0.149	3.61	0.115	0.405
CSP transformer	3,215	64.2	0.172			0.234	0.018	0.018	0.106	0.127*	0.074	0.112

* Deion gap failures per 100 installations.

Table XIV. Combined Operating Data on Various Methods of Protecting Distribution Transformers From Lightning for 1935 and 1936

Rural Installations

Type of Protection	Average Number Installations	Average Ground Resistance (Ohms)	Failures per 100 Installations									
			Primary Fuses Blown			Transformer Windings Damaged					Customers'	
			Total	Lightning Arrester on Line Side of Fuse	Lightning Arrester on Transformer Side of Fuse	Total	Primary Only	Secondary Only	Primary and Secondary	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	17,756	106	12.17	11.45	N.D.	0.691	0.259	0.175	0.278	2.90	2.25	0.301
Solid interconnection with and without tie to case	4,903	18.2	5.26	4.88	5.39	1.55	0.066	0.022	0.088	0.932	0.572	0.215
Gapped interconnection with and without tie to case	13,408	46.3	10.63	5.83	13.70	0.714	0.691	0.067	0.780	1.07	2.06	0.075
Common primary and secondary neutral	3,383	13.7	6.28	1.32	8.98	0.358	0.129	0.032	0.193	0.392	0.166	0
Surge-proof transformer	832	52.2	8.53			0.361	0.131	0	0.197	0.945*	0	0.075
Three-point protection	219	47.5	9.81	18.60	N.D.	0.456	0.228	0	0.228	9.75	0	0.772
CSP transformer	834	89.5	0.376			0	0	0	0	0.198*	0.123	0.135

* Deion gap failures per 100 installations.

Table XV. Combined Operating Data Upon Various Methods of Protecting Distribution Transformers From Lightning for 1935 and 1936

Urban and Suburban Installations

Type of Protection	Average Number Installations	Average Ground Resistance (Ohms)	Failures per 100 Installations									
			Primary Fuses Blown			Transformer Windings Damaged					Customers'	
			Total	Lightning Arrester on Line Side of Fuse	Lightning Arrester on Transformer Side of Fuse	Total	Primary Only	Secondary Only	Primary and Secondary	Lightning Arrester Failures	Meters Burned Out	Wiring, Etc., Damaged
Standard connection	105,029	76.6	3.34	3.11	5.80	0.687	0.228	0.056	0.290	0.465	0.731	0.063
Solid interconnection with and without tie to case	74,637	10.2	1.05	0.552	1.90	0.185	0.031	0.028	0.073	0.174	1.91	0.104
Gapped interconnection with and without tie to case	1,876	61.3	6.75	1.87	3.89	0.464	0.121	0.030	0.303	0.460	1.16	1.19
Common primary and secondary neutral	26,670	8.3	0.749	0.438	3.96	0.180	0.053	0.003	0.030	0.337	0.378	0.100
Surge-proof transformers	325	33.4	9.47			0.462	0.154	0	0.308	0.156*	0.167	0.168
Three-point protection	429	8.0	3.57	N.D.	N.D.	0.350	0.117	0.117	0.117	1.71	0.122	0.792
CSP transformers	396	49.5	0.214			0.253	0	0	0.253	0.127	0	0.370

* Deion gap failures per 100 installations.

Table XVI. Effect of Ground Resistance Upon Operating Data for Various Methods of Protecting Distribution Transformers From Lightning—1934, 1935, and 1936 Lightning Seasons

All Types of Territory

Type of Protection	Range of Average Ground Resistance (Ohms)	Average Number of Installations	Number of Companies 1934	Number of Companies 1935	Number of Companies 1936	Failures per 100 Installations: Primary Fuses Blown	Failures per 100 Installations: Transformer Windings Damaged	Failures per 100 Installations: Lightning Arrester Failures	Failures per 100 Installations: Customers' Meters Damaged	Failures per 100 Installations: Customers' Wiring, Etc., Damaged
Standard connection (figure 1)	1– 10	17,166	3	4	4	3.50	0.425	0.930	0.653	0.625
	11– 20	25,542	5	8	4	3.82	0.743	0.432	2.00	0.084
	21– 30	7,376	3	2	5	3.34	0.344	0.262	0.316	0.168
	31– 40	9,051	2	3	2	2.92	0.558	0.188	0.495	0.069
	45– 75	5,477	1	5	4	5.91	1.31	0.711	1.92	0.129
	80–125	28,181	4	0	0	10.4	0.92	2.67	0.996	0.883
	200–250	9,772	2	2	1	20.5	1.26	3.84	1.47	0.101
Solid interconnection (figures 2 and 3) and common primary and secondary neutral (figure 6)	0– 1	40,761	7	6	10	0.545	0.112	0.256	1.43	0.050
	2– 5	13,291	5	8	6	1.35	0.216	0.199	0.272	0.100
	6– 10	29,585	4	3	6	1.91	0.260	1.49	0.211	0.152
	11– 20	22,375	0	6	4	6.65	0.410	0.480	0.236	0.043
	21– 30	4,077	5	3	4	1.84	0.163	0.143	0.019	0.039
	50–133	6,858	2	2	0	18.52	0.74	0.484	0	0
Gapped interconnection (figures 4 and 5)	0– 10	921	2	2	3	3.40	0.217	0.094	0	0.080
	11– 20	5,439	0	4	2	13.90	0.792	1.35	0.81	0.101
	21– 30	1,724	1	2	8	10.70	0.600	1.28	0.726	0
	31– 50	542	1	1	1	11.50	1.23	1.54	1.29	0.064
	51–100	1,030	0	2	2	5.96	2.09	1.36	3.74	0
	101–250	516	1	1	1	2.91	0.324	0.453	0	.259
Surge-proof transformers (figures 7 and 9)	1– 25	761	7	8	6	1.75	0.657	0.228*	0	0
	26–100	857	5	3	6	6.45	0.272	0.823*	0.185	0.063
	101–400	378	2	4	1	7.40	0.176	2.03*	0	0.176
Three-point protection (figure 8)	1– 10	150	2	1	2	5.70	0.89	1.60	0.320	0.970
	11– 20	121	1	1	1	1.54	0.55	0	0	0.276
	21– 30	35	1	0	1	4.35	0	4.35	0	0
	70– 80	86	1	1	0	13.95	0	16.87	N.D.	0.91
	175	723	0	1	0	3.60	0.969	1.24	0	0

* Deion gaps damaged per 100 installations.

Table XVII. Effect of Ground Resistance Upon Operating Data for Various Methods of Protecting Distribution Transformers From Lightning—1934, 1935, and 1936 Lightning Seasons

Rural Installations

Type of Protection	Range of Average Ground Resistance (Ohms)	Average Number of Installations	Number of Companies 1934	Number of Companies 1935	Number of Companies 1936	Failures per 100 Installations: Primary Fuses Blown	Failures per 100 Installations: Transformer Windings Damaged	Failures per 100 Installations: Lightning Arrester Failures	Failures per 100 Installations: Customers' Meters	Failures per 100 Installations: Customers' Wiring, Etc., Damaged
Standard connection (figure 1)	1– 30	4,976	2	2	6	3.09	0.173	0.45	0.52	0.01
	40– 70	712	1	1	3	27.9	2.30	2.94	10.43	0.423
	71–100	164	2	0	1	11.30	2.75	N.D.	1.81	N.D.
	200–250	4,686	0	2	1	11.70	0.45	4.07	2.70	0.160
All types of interconnection (figures 2, 3, 4, 5, and 6)	0– 10	7,533	0	0	13	4.46	0.44	0.73	0.18	0.19
	11– 20	7,207	0	6	3	12.10	0.62	1.10	0.64	0.08
	21– 30	2,130	3	3	7	8.49	0.58	1.12	0.34	.09
	31– 50	1,588	1	2	4	20.9	2.98	0.73	0.80	0
	51– 60	283	0	1	0	3.53	0.71	1.77	0	0
	75– 90	563	0	2	2	11.20	3.02	1.87	5.50	0
	101–250	195	1	0	1	4.89	0	0.34	N.D.	0
Surge-proof and *CSP* transformers (figures 7 and 9)	1– 25	131	4	6	1	1.35	0	0.51	0	0
	26–100	696	3	2	6	5.79	0.24	0.98	0.13	0
	101–400	418	2	5	0	9.10	0.272	2.62	0	0.12
Three-point protection (figure 8)	1– 10	20	1	0	0	5.00	5.00	0	0	0
	11– 20	95	1	0	1	1.05	1.05	0	0	0.53
	21– 30	35	1	0	1	8.57	0	8.57	0	0
	70– 80	94	1	1	1	17.00	0	12.10	N.D.	N.D.

of interconnection. The data in table XVI show the reverse trend when the standard connection and solid interconnection only are compared. This leads to the conclusion that a large part of the improvement noted by the use of solid interconnection is the result of the lower values of ground resistance that almost invariably exists when the latter is used.

EFFECT OF OPERATING VOLTAGE

An analysis of the data by operating voltage has been made in tables XVIII, XIX, and XX. In drawing this comparison allowance has been made for type of territory, ground resistance, and location of primary fuse. Due to lack of data no comparison could be drawn for urban and

Table XVIII. Effect of Operating Voltage and Average Ground Resistance on Operating Data for Various Methods of Lightning Protection—1935 and 1936 Lightning Seasons

All Types of Territory

Type of Protection	Range of Average Ground Resistance (Ohms)	Average Number of Installations			Failures per 100 Installations																	
					Primary Fuses Blown						Transformer Windings			Lightning Arresters			Customers' Meters Burned Out			Customers' Wiring, Etc., Damaged		
					Lightning Arrester on Line Side of Fuse			Lightning Arrester on Transformer Side of Fuse														
		1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv
Standard connection (figure 1)	1–10	18,392	523*	101*	2.58	20.6	28.8	N.D.	N.D.	N.D.	0.283	0.382	1.98	1.13	N.D.	N.D.	0.352	N.D.	N.D.	0.625	N.D.	N.D.
	11–25	22,408	4,026	945	2.00	10.2	7.45	N.D.	N.D.	N.D.	0.577	0.475	0.423	0.485	2.99	1.89	1.70	N.D.	0	0.162	N.D.	N.D.
	26–50	7,875			2.46			N.D.			0.665			0.489			0.064			0.021		
	51–100	10,695			3.54			N.D.			0.705			0.206			0.424			N.D.		
	200–250	7,945			6.86			2.52			0.315			2.28			1.47			0.082		
Solid interconnection with and without tie to case (figures 2 and 3)	0–1	39,754			0.725			1.17			0.114			0.167			1.67			0.036		
	1–5	9,541			0.926			0.875			0.152			0.352			0.067			0.187		
	6–10	23,520			1.39			1.20			0.047			0.089			0.25			0.122		
	11–20	27,398	930	1,049	14.1	N.D.	0	8.25	N.D.	6.30	0.545	0.645	0.191	1.50	N.D.	1.07	6.86	0	0.048	0.336	0	0
	21–30	501			3.51			1.11			0.40			0.85			N.D.			0.200		
Gapped interconnection with and without tie to case (figures 4 and 5)	0–10	1,515	None	11*	3.96		15.40	2.18		11.1	0.278		4.55	0.132		0	N.D.		0	0.080		0
	11–20	None	None	139			10.00			58.5			0			0			0			0
	21–30	5,168	None	58*	1.92		10.00	1.40		30.3	0.773		3.03	0.958		N.D.	0.135		N.D.	0.106		N.D.
	50–75	702	83*	266	6.19	N.D.	1.43	N.D.	1.67	N.D.	2.78	2.41	3.76	1.14	0	3.76	1.07	0	0	N.D.	0	0
	75–100	573	None	None	N.D.			N.D.			0.349			2.10			2.62			0		
	250	725	None	None	N.D.			2.48			0.345			0.483			N.D.			0.276		
Common primary and secondary neutral (figure 6)	0–5	14,195	None	None	0.328			N.D.			0.127			0.440			0.517			0.138		
	6–10	504*	None	None	0			N.D.			0			0.20			N.D.			N.D.		
	11–20	None	None	2,111			N.D.			9.13			0.284			0.412			0.412			0
	21	4,600*	None	None	0.413			N.D.			0.065			0.043			0			0		
Westinghouse surge-proof transformers (figure 7)	0–25	187	38	None	0	15.5					0.266	0		0	0		0	0		0	0	
	26–100	38	24	None	10.52	20.8					2.63	0		0	0		0	0		0	0	
	100–150	927	None	None	20.5						0.54			2.48			N.D.			0.108		
Westinghouse *CSP* transformers (figure 9)	0–10	106	None	7*	0		14.28				0.47		0	0.5		0	0		N.D.	0		N.D.
	11–25	19	207	None	0	N.D.					0	0		5.26	0		0	0		0	0	
	26–50	None	43*	45*		0	2.22					0	2.22		0	2.22		0	0		N.D.	0
	51–75	155	None	None	0						0			0			0			0		
	250	22	None	None	0						0			0			0			0		

* Based on report of only one company for either one or two years.

Insufficient data for tabulation on three-point protection—figure 8.

suburban installations for voltages above 5 kv (see table XX). It is thought that the data indicates that in spite of the paucity of data the trouble rates are higher for the higher distribution voltages.

Location of Transformer Winding Failures

Where possible data were obtained relative to the location of transformer-winding failures, i.e., whether the primary only, the secondary only, or both the primary and secondary were involved in the failure. While with some types of protection a sufficient number of failures to indicate trends have not been reported, a sufficient number have been reported for several types of protection. These data have been summarized in table XXI. Except for the gapped interconnection, the *SP* and *CSP* transformers in which cases relatively few failures were reported, the various types of protection show consistent trends.

Secondary Protection

Since the average data in table XXI show that in 64.8 per cent of the transformer winding failures the secondaries are involved, the question arises as to whether or not this high percentage may be due to the lightning surges entered from the secondary. A secondary-winding failure does not necessarily mean a secondary entrance of the surge as a surge entering through the primary in its attempt to reach the

Table XIX. Effect of Ground Resistance Upon Operating Data for Various Methods of Protecting Distribution Transformers From Lightning—1935 and 1936 Lightning Seasons

Rural Installations

Type of Protection	Range of Average Ground Resistance (Ohms)	Average Number of Installations			Failures per 100 Installations																	
					Primary Fuses Blown																	
					Lightning Arrester on Line Side of Fuse			Lightning Arrester on Transformer Side of Fuse			Transformer Windings Damaged			Lightning Arrester Failures			Customers' Meters Burned Out			Customers' Wiring, Etc., Damaged		
		1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv	1–5 Kv	6–10 Kv	11–15 Kv
Standard connection (figure 1)	7– 15	None	342	188		N.D.	13.89		N.D.	N.D.		5.42	0.534		2.99	N.D.		N.D.	0		N.D.	0
	21– 30	2,082	None	371*	5.38		N.D.	N.D.		N.D.	0.337		0.270	0.720		1.89	N.D.		0	0		N.D.
	31– 40	None	350*	None		18.00			N.D.			2.86			3.43			N.D.			N.D.	
	68– 75	160	None	None	15.53			N.D.			2.10			1.84			1.58			0		
	200–250	3,721	None	None	11.35			5.40			0.43			4.07			2.70			0.134		
All types of interconnection	0– 10	2,418	None	2,068	3.04		N.D.	2.45		6.24	0.394		0.195	0.580		1.06	0.400		0.048	0.329		0
	11– 20	5,319	None	3,777	4.61		10.0	14.4		10.30	0.743		0.265	0.969		0.715	0.142		0.476	0.111		0
	21– 30	786	None	116	3.16		10.0	3.00		30.30	0.382		3.03	0.792		0	0		0	0.127		0
	50– 60	200*	1,214	563	N.D.	N.D.	14.3	N.D.	1.6	N.D.	0	2.51	6.59	2.50	0	3.76	0	0	0	0	0	0
	75– 90	563	None	None	12.31			N.D.			3.02			1.87			5.50			0		
	250	291*	None	None	N.D.			3.44			0			0.344			N.D.			0		

Insufficient data for tabulation on *SP* and *CSP* transformers and three-point protection.
* Based upon single company for either one or two years.

ground may flash over a secondary bushing and raise the potential of the secondary winding sufficiently to cause it to fail. On the other hand the rate of meter failures per hundred transformers shown in tables X to XV indicate the possibility of surges on the secondary.

Of the companies reporting six report the use of secondary protection. In most of these cases secondary protection is used in a few installations apparently as an experiment. However, one company makes it a practice to install secondary arresters on polyphase meters and another company installs secondary arresters at customers where electric ranges are installed.

EFFECT OF FUSING SCHEDULE

Since the primary fusing schedule used by any company cannot be expressed in a single numerical statement, any comparison must be only approximate. In making the comparison in table XXII an attempt has been made to reduce all the fusing schedules to a percentage basis. In spite of the fact that no definite trend is established it is believed that irrespective of the type of protection used the rate of primary fuses blown should decrease with the use of higher rated fuses. This has been borne out by studies made by several individual companies.

EFFECT OF LOCATION OF PRIMARY FUSE

As a result of the question raised regarding the effect of the surge current causing the primary fuse to blow, the data have been analyzed in tables XIII to XV showing the rates of fuse blowing when the primary fuse is installed on the line side of the arrester separate from those when the fuse is installed on the transformer side of the arrester. From a study of these tables it is apparent that with all types of protection the rates of primary fuses blown are higher when the arrester is on the transformer side of the fuse and the surge current passes entirely through the fuse.

EFFECT OF ONE OR TWO FUSES PER TRANSFORMER

In three-phase four-wire systems it is customary to connect single-phase transformers between phase and neutral using a single fuse; whereas in three-phase three-wire systems single-phase transformers must be connected between phases necessitating two fuses per transformer. In table XXIII a comparison is drawn to determine whether or not there is any difference in the number of fuses blown per hundred transformers when one or two fuses per transformer are used. The data show that the rates of primary fuses blown are practically the same in both cases.

GROUNDING OF TRANSFORMER TANKS

Since theory, laboratory tests, and certain field data indicate that if the transformer tank is left free to assume any potential a greater strain may be imposed upon the insulation by lightning surges than if the tank were held at ground potential, a growing tendency to ground the tanks of distribution transformers is noted. Fourteen of the companies reporting state that they ground the transformer tanks on some 40,437 transformers. Seven

Table XX. Effect of Ground Resistance Upon Operating Data* for Various Methods of Protecting Distribution Transformers From Lightning—1935 and 1936 Lightning Seasons

Urban and Suburban Installations

Type of Protection	Range of Average Ground Resistance (Ohms)	Average Number of Installations	Failures per 100 Installations					
			Primary Fuses Blown					
			Lightning Arrester on Line Side	Lightning Arrester on Transformer Side	Transformer Windings Damaged	Lightning Arrester	Customers' Meters	Customers' Wiring, Etc.
Standard connection (figure 1)	1– 10	19,657	1.70	N.D.	0.333	1.04	N.D.	N.D.
	11– 15	9,716	2.18	N.D.	0.710	0.653	1.89	0.085
	16– 20	11,605	3.51	N.D.	0.860	N.D.	N.D.	N.D.
	21– 30	4,510	1.10	N.D.	0.266	0.213	0.482	N.D.
	31– 50	5,867	1.66	N.D.	0.698	0.595	0.038	0.038
	70–100	10,501	3.32	N.D.	0.680	0.176	0.317	N.D.
	200	7,336	2.34	N.D.	0.177	0.819	N.D.	0.028
	250	567	N.D.	1.41	0.176	0	1.06	0
All types of interconnection (figures 2, 3, 4, 5, and 6)	0– 1	47,291	0.638	7.90	0.115	0.184	0.570	0.021
	1– 3	11,542	0.378	0.751	0.100	0.332	0.145	0.186
	4– 10	8,282	1.08	1.20	0.179	0.376	1.32	0.715
	11– 30	12,959	0.580	1.05	0.555	0.049	0	0
	50	6,364	N.D.	N.D.	0.188	0.487	N.D.	N.D.

* This data for 0–5 kv only; insufficient data for tabulation for 6–15 kv.
Insufficient data for tabulation on three-point protection, surge-proof and *CSP* transformers.

Table XXI. Location of Transformer Winding Failures Expressed as Per Cent of Total Failures—1935 and 1936 Lightning Seasons Combined

All Types of Territory

Type of Protection	Number of Segregated Transformer Failures	Per Cent Primary Only	Per Cent Secondary Only	Per Cent Primary and Secondary
Standard	685	35.8	11.1	53.1
Solid interconnection	307	29.6	13.4	57.0
Solid interconnection with tie to case	7	28.6	28.6	42.8
Gapped interconnection	65	29.2	6.2	64.6
Gapped interconnection with tie to case	27	74.1	7.4	18.5
Common primary and secondary neutral	53	51.0	5.6	43.4
Surge proof	17	17.6	17.6	64.8
Three-point protection	12	58.3	16.7	25.0
CSP	8	12.5	12.5	75.0
Total	1,181	35.2	11.3	53.5

Table XXII. Effect of Fusing Schedule on Number of Primary Fuses Blown—1935 and 1936 Data Combined

Fuses on Transformer Side of Lightning Arrester

Schedule Range (Per Cent)	Standard Connection		Interconnection (All Types)	
	Number Installations Involved	Per Cent Primary Fuses Blown	Number Installations Involved	Per Cent Primary Fuses Blown
150–200	26,134	3.78	Insufficient data	
201–250	20,324	4.60	57,221	1.43
251–300	31,835	4.30	3,173	2.27
301–400	Insufficient data		36,300	1.39
401–500	1,517	3.89	Insufficient data	

companies ground the tanks on 18,478 transformers protected with the standard connection. Six companies do the same on 2,684 transformers using solid interconnection. Three companies ground the tanks on 1,340 transformers using gapped interconnection. Nine companies using the common primary and secondary neutral ground the tanks on 17,935 transformers.

LIMITATIONS PLACED ON GROUND RESISTANCE

Since the data indicate that the value of resistance of the arrester ground is a factor of major importance in rendering effective lightning protection, the practice of the various companies in reducing or placing limitations on ground resistance has been analyzed in table XXIV. Of the 44 groups of installations of the standard connection only 15 make any specific attempt to lower or to limit the ground resistance. On the other hand only seven groups of installations of solid interconnection have no limitation on the ground resistance of which five have grounds salted. Of the 33 groups of installations of solid interconnection 13 have definite limitations

Table XXIII. Difference Upon Rate of Primary Fuses Blown Due to One or Two Primary Fuses per Transformer—1935 and 1936 Data Combined

Type of Protection	One Fuse per Transformer Installation		Two Fuses per Transformer Installation	
	Average Number Installations	Fuses Blown per 100 Transformers	Installations	Fuses Blown per 100 Transformers
Standard	43,080	5.60	27,574	5.22
Solid interconnection	55,200	0.945	34,630	1.84
Solid interconnection with tie to case	103	2.91	1,808	1.66
Gapped interconnection	7,516	10.4	3,950	7.80
Gapped interconnection with tie to case	0	N.D.	483	28.60*
Type *SP* transformer	1,302	6.72	504	4.66
Three-point protection	293	7.85	617	3.72
Type *CSP* transformer	640	0.08	261	0.19
Total—all types	108,134	3.54	69,827	3.74

* Based on one company which had much damage done by a severe storm during 1936.

Table XXIV. Ground Resistance Limitations Placed Upon Various Schemes of Lightning Protection—1935 and 1936 Data

	Standard Connection	Solid Interconnection	Solid Interconnection Tie to Case	Gapped Interconnection	Gapped Interconnection Tie to Case	Common Primary and Secondary Neutral	Surge-Proof Transformers	Three-Point Protection	CSP Transformers
Installation Groups Reported Upon	44	33	6	24	4	20	21	7	25
Number reducing ground resistance to specified value:	15	13	1	7	2	6	5	2	6
200 ohm					1				
100 ohm	1					1			
50		2	1	2					
30	2	1		1				1	1
25	6	3		2		1	3	1	2
20					1				
15	4	3		1		1	2		2
10		3		1					
5						2			1
Less than 5	2	1				1			
By salting only	1			1					1
Water pipe grounds	1	3							
Driven grounds	4	3		1		3	3	1	2
Salting and water pipes		2							
Salting and driven grounds	5		1	2	2	1	1	1	1
Water pipe and driven grounds		1				1			
No method	4	4		3		1	1		2
Number specifying water pipes only:	1	5	2	2	1	1			
1	1	2							
2		1	1	1		1			
3		2		1	1				
4									
5									
Number specifying driven grounds only:		5	1	8			3		1
1		1	1	6			1		
2		1		2			1		1
3		3					1		
Number specifying either water pipe or driven grounds:									
One water pipe, two driven		3							
Two water pipe, one driven		2							
Two water pipe, two driven		1							
Number salting grounds without limitation as to resistance		3		1	1		1		3
Number salting grounds and driving rods without limitation as to resistance	1	2		2		1	1	1	1
No limitation	27	2	2	4		12	11	4	14
Number placing limitation because of:									
Experience		8	1	4	1				
National Electrical Code		3		5					
Both		1		3					

N.B. Installation group does not necessarily mean company. Some companies impose limitations upon certain territories or certain voltages.

of the maximum value of ground resistance, eight require water pipe grounds, and four require more than one driven ground.

Discussion

Herman Halperin (Consolidated Edison Company, Chicago, Ill.): While analysis of extensive data involving numerous variables generally proves difficult, Smith has done a commendable job. The large number of tables, which at first seems confusing, presents the data in such a way as to make further analysis readily possible.

From the standpoint of protection to equipment, it is of interest to examine the combined rates of transformer winding failures and fuse blowings. The combined figures for 1935 and 1936, expressed as the ratio of transformer and fuse troubles to similar troubles with the solid interconnection, were: common neutral, 1.3; standard connection, 3.4; gapped interconnection, 5.8. For the remaining protective schemes, including the self-protecting types of transformers, the numbers of installations involved were statistically insufficient, that is, only a few per cent of the number with solid interconnection, and definite conclusions for these types appear unwarranted as yet.

In view of the fairly extensive application of the gapped interconnection, it must be disturbing to a number of companies to learn of the generally poor performance of this protective scheme. With this connection, the surge voltage impressed on the transformer is that permitted by the phase arrester plus the drop in connecting leads and plus the breakdown of the spark gap. This latter value may be about the same as the voltage across the lightning arrester. Two alternative improvements may be suggested for such installations: (*a*) reduction in breakdown voltage of the interconnection gap, by the use of lower rated or special gaps; or (*b*) a change to the solid interconnection. The objection to this latter connection was based mainly upon fear for the customers' safety, but, according to our Chicago studies ("Lightning Investigations on a Distribution System," Halperin and Grosser, ELECTRICAL ENGINEERING, January 1936, pages 63–70) and the data in this paper, this objection to solid interconnection is of no consequence and should gradually disappear.

Conclusion 3 of the paper, indicating that the rate of arrester failures is lower with solid interconnection than with the standard connection, is based on a general averaging of the data from all companies. This conclusion does not seem to be entirely justified by the data, when the operating records of individual companies are considered. Of 12 companies, which report on a sufficiently large number of installations of both types to be suitable for comparison, seven, including Chicago, showed higher rates of arrester failure with the solid interconnection than with the standard connection. Theoretically, some increase in failure rate should be expected with solid interconnection, because of the greater duty on the arrester in discharging surge current to a low resistance ground. The best way to determine the effect of one variable is to have just one variable in the study, and that was the case in Chicago when we had both solid interconnection and standard connection of arresters for a few years over various parts of the city and found that arrester failures were relatively high with the solid interconnection.

The installation of the solid interconnection in Chicago was very much cheaper than trying to improve the ground resistance with the standard connection. The solid interconnection was obtained simply by the installation of a short piece of Number 6 wire between the ground side of the arresters and the secondary neutral. The effect of the solid interconnection in Chicago was to reduce the total rate of transformer failures and fuse blowings by over 50 per cent as compared to the rate that obtained with the standard connection of arrester.

Regarding conclusion 8, while it is recognized that the majority of the reported installations of secondary arresters were of an experimental nature, it would be of interest to learn something of the reasons for providing these protective measures.

The compilation of a large amount of data such as this may make it possible to analyze the effect of thunderstorm frequency on lightning troubles. It is suggested that the next questionnaire circulated should be modified to determine, for the four years beginning with 1934, the number of thunderstorms per year, both from weather bureau and company records, and an attempt made to correlate these data with lightning trouble rates.

W. A. McMorris (General Electric Company, Pittsfield, Mass.): Mr. Smith and those who have co-operated with him in the accumulation and analysis of operating data on distribution circuits, are to be congratulated on what they have accomplished. Differences in the types and ages of equipment in use, and in the conditions under which it must operate, require a study of broad scope in order that definite trends in performance may be established.

The data obtained have made it possible to draw a number of conclusions with regard to best operating practices. A few inconsistencies still remain, but it is to be expected that these will decrease in number as the investigation is continued.

On page 5 of the preprint it is stated that "the fear that has been expressed that with solid interconnection a heavier duty may be placed on the arrester causing more failures is without foundation." This conclusion is well supported, without contradictions, by data in tables X to XV, inclusive. Table X which summarizes the results, shows an arrester failure rate of 1.17 per hundred for 159,138 installations with standard connection, and only 0.551 per hundred for 146,738 installations with solid interconnection. Rather than increasing the arrester failure rate, solid interconnection has reduced it to 47 per cent of the value for standard connection, and to 57.5 per cent of the value for gapped interconnection, the nearest competitor in this table.

Information given in recent AIEE papers by Mr. Flanigen ("Lightning Protection of Distribution Transformers," AIEE TRANSACTIONS, volume 54, pages 1400–05, December 1935) and by Messrs. Halperin and Grosser ("Lightning Investigations on a Distribution System," AIEE TRANSACTIONS, volume 55, pages 63–70, January 1936) suggests that many arrester failures result from other causes than high-current lightning discharges. This was borne out in the investigation reported in the paper by Mr. McEachron and myself, presented at this convention, in which measurements were made of the discharge currents associated with arrester failures. Figure 11 of that paper shows a very small percentage of arrester failures to be due to high discharge currents.

The obvious conclusion is that solid interconnection probably does result in some increase in the magnitude of currents passed by arresters, but that high current discharges are not a major cause of arrester failure, so the predicted increase in arrester failure rate does not occur. Interconnection may result in an increase in arrester discharge currents by lowering ground resistances, but this tends to localize the disturbance so that fewer arresters operate.

This possibly helps to explain the lower arrester failure rate with solid interconnection. Failures from power current resulting from sixty-cycle overvoltage, gap corrosion, or similar causes, would decrease as the number of arrester operations is decreased by localizing the disturbances, more or less independently of any change in the magnitude of lightning discharge currents.

In general, the performance of the various gapped interconnections, including three-point protection and surgeproof transformers, has been considerably less satisfactory, even though the surgeproof transformers and their deion gaps were all new equipment. The protective scheme of the surgeproof transformer is essentially a gapped interconnection, and the over-all service performance from table X does not appear to be greatly out of line with that of other gapped interconnections.

Since the paper reports field data for 1934, 1935, and 1936, the surgeproof transformers referred to are presumably of the type with the deion gap inside the transformer tank. With such a protective device inherently a part of the transformer, either winding failure or gap failure would probably require transformer removal and maintenance.

Table X, summarizing all data, shows 1.21 gap failures and 0.43 winding failures per hundred installations of surgeproof transformers, compared to values of 0.551 and 0.350, respectively, for conventional transformers protected by valve-type arresters with solid interconnection. In some cases, both gap and winding failures may have occurred on the same transformers, so the number of surgeproof transformers requiring maintenance, per hundred installed, would be between 1.21 and 1.64. For solid interconnection with valve-type arresters mounted outside the transformer tank, arrester failure alone does not make transformer replacement or maintenance necessary, and only 0.350 transformers per hundred installed would have to go to the shop. Thus for the surgeproof transformers, all of which were relatively new, maintenance was required from 3.5 to 4.7 times as often as for the older standard transformers with solidly interconnected arresters. Both table XI showing data from rural circuits, and table XII showing data on urban and suburban circuits, but which are based on many fewer installations than table X, indicate that more transformer maintenance is required for surgeproof transformers than for standard transformers with solid interconnection.

Such an analysis based on the data reported in the paper, shows that distinct disadvantages result from combining the protective device with the transformer in such a way that the failure of the protective device is likely to interrupt service of the transformer or require its removal for maintenance. Similarly it is shown that the full benefits of interconnection are not realized by any of the schemes in which the interconnection is made through a gap.

F. E. Andrews and **R. O. Askey** (Public Service Company of Northern Illinois, Chicago, Ill.): As a result of a brief study of the data in this paper made within the short time during which a printed copy has been available, it appears that there are several factors which may influence the various failure rates and which may be of greater importance in the results shown by the different types of protection than the inherent differences in the protective scheme.

It is noted in table X summarizing results of all types of territory that the rate of primary fuses blown is in general higher with the gapped interconnection than either the solid interconnection or standard connection. It is also noted by reference to table XI that 82 per cent of the total number of gapped interconnection installations are classified as rural and that for the rural installations there is less difference in performance of the gapped installation in comparison with the others. As noted in the text of the paper, the failure rate for the rural installations for all types of protection is apparently considerably higher than for urban, which suggests that differences in exposure, arrester density, etc., which are inherent in the nature of the territory probably have a considerable influence.

We have noted in studies of our operating data with respect to the interconnection, much the same relationship with respect to the gapped interconnection as is indicated by the data in the paper. We have also noted in attempting to explain the apparent failure of the gapped interconnection to perform as satisfactorily as the solid interconnection that the gapped interconnection in general has been used in a much larger proportion of situations where grounding conditions are less satisfactory and where specific trouble due to fuse blowing has been previously experienced. This trouble due to the larger amount of fuse blowing has been found in many instances to have been due to inadequate lead and bushing insulation such that even with the interconnection satisfactory co-ordination with the lightning arrester could not be obtained. Under this condition it has been apparent that material improvement by the use of the interconnection could not be expected.

It would accordingly seem that if data on the various types of protection are to be compared purely on the merits of the various protective schemes it is necessary that the transformers involved also be classified in such a manner as to factor out those of known susceptibility to trouble of this nature. The principal items affecting this susceptibility are probably transformer size, age, and manner in which maintenance and repair work have been done. In line with this idea it would seem advisable to set up a separate grouping to include only transformers built according to present day standards which in general would probably include those bought since about 1934.

In furtherance of this idea we have made a partial study of performance of these newer transformers and while at the present time we cannot give specific data on them with reference to the different types of protection, it is obvious that rates of failure substantially different from those applying to the older transformers on the system will be found. One apparently significant point has been developed thus far from this investigation. It was believed that with new transformers of adequate design with respect to leads and bushings, it should be relatively easy to determine the explanation for each case of fuse blowing. We accordingly investigated the record of 41 cases of fuse blowing in a group of 672 modern transformers in the size range from one and one-half to seven and one-half kva, inclusive. The results of this investigation are shown as follows:

Number of transformers in group	672
Total number of fuse operations	41
Number of installations at which fuses were blown	39
Number of installations inspected in detail. (The arresters were connected to the line side of the fuse on all of these installations.)	13
Installations showing evidence of lead or bushing flashover	5
Installations at which no evidence was found to explain the fuse operations	8

From this data it is evident that there were a few cases in which transformer fuses were blown due to bushing flashovers in spite of the lightning arrester protection. There were, however, eight cases in which no ordinary explanation of the fuse blowing was evident. The transformers at these eight locations at which fuse blowing occurred were given the standard AIEE high-potential tests to determine if fuse blowing might have been caused by a coil puncture which was sealed off, perhaps by the transformer oil. All of these transformers stood the high-potential test successfully, indicating that the fuse failure occurred without passage of fault currents through the fuse.

An investigation, now in progress, of the performance of a similar group of modern transformers has disclosed that a number of instances of fuse blowing without leaving visible evidence of the path of the current responsible have occurred. In general these have been at rural installations using three- and five-ampere fuses and with the lightning arresters connected to the line side of the cutout. For the most part, these have been confined to gapped interconnected installations in rural territory.

These data point to the likelihood of the fuse blowing being due to some other type of current through the primary fuse not heretofore recognized in connection with distribution transformers such as perhaps transients due to capacity coupling from primary winding to secondary or to core and tank. There is also the possibility of high current in the fuse due to resonance between the inductance of the transformer and the capacity of the interconnection gap. It is believed that with modern transformers, at least in the smaller sizes, a relatively large proportion of fuse blowings is due to the effect described above and that it is important to direct any future investigation toward an explanation of this effect.

W. G. Roman (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): This report has tabulated a large mass of data on distribution transformer lightning-protection practice. Since these data were taken from a large number of operating companys they represent an interesting cross section or average practice.

An examination of table X shows the solid interconnection gives the best all around lightning protection although the meter burnouts are relatively high. These data are somewhat conflicting since the damage to customer's wiring is the lowest for the solid interconnection. The reasons for the low arrester failure rate for the solid interconnection are not obvious. Because of the lower effective ground resistance of the interconnection the surge currents discharged by the arrester should be higher and should result in a higher arrester failure rate. The lower rate shown in the table may be because installations having the solid interconnection also on an average have more modern arresters.

Table XVI shows that for the standard connection the low ground resistance is definitely desirable in reducing trouble. For the various forms of interconnection this is not apparent which checks with what is to be expected since in the interconnection schemes the ground drop is not added to the voltage appearing across the protective device. The reason for the high meter-failure rate for the solid interconnection for ground resistances of zero to one ohm is not apparent unless these low ground resistances are usually obtained by tying the secondary neutral to the water system on the customer's premises. If this were true, the major portion of the surge would be discharged through the customer's ground and might result in a higher meter-failure rate. This is borne out by table XVII which shows a low meter-failure rate for rural installations having a low ground resistance.

Frank Sanford (Cincinnati Gas and Electric Company, Cincinnati, Ohio): Perhaps the most important conclusion of this paper is that interconnection of grounding on distribution transformer installations is an established practice. The general data confirm the data that individual utilities have that this form of protection has accomplished a great deal and that its continuation and extension is justified. Three detailed comments may be noted:

1. The increase that is noted in the paper in grounding of the transformer tanks may be due more to the use of rural-type transformers rather than any change in policy on urban type installations.

2. The relationship between fusing schedule and per cent blown fuses caused by lightning is not shown in the paper. Its importance may justify a more detailed study and the economics of failure and service outages may justify a higher fuse schedule, especially on the smaller size transformers.

3. It would seem better not to group together all systems using one to five kv distribution, in comparing standard connection and interconnection. Of twenty companies, only four failed to show a large reduction in both transformer failures and fuses blown, with the interconnection method. Of these, one showed an increase in fuses blown but they operate with the arrester on transformer side of fuse and they may not fuse high enough for this condition. The other three operate a 4.8-kv delta system. Other records indicate a higher trouble experience with 4,150 volts or 4,800 volts than with the 2,400/4,150-volt system, other conditions being equivalent, and this would seem to justify the break-down of the records in comparison of this kind.

J. K. Hodnette (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Mr. L. G. Smith is to be complimented on the fine job he has done collecting and compiling the data on distribution transformer lightning protection. Data of this type should prove very valuable to distribution engineers in working out the problem of lightning protection to distribution transformers.

It is possible that some of the inconsistent results obtained to date could be explained if more were known of the operating conditions surrounding the transformers. It would be desirable to tabulate the storm days per year experienced by each company reporting. In this manner the results obtained by different operating companies could be more accurately compared as well as the year to year results of individual companies.

It would be desirable to establish a more accurate nomenclature for the different methods of protection. Referring in particular to figure 8 in the paper which is designated as "three point protection," this phrase was originated by Mr. Fred Hanker to designate a type of protection in which the protective devices joined the high-voltage winding and low-voltage winding and the tank together, such as is illustrated in the author's figures 3, 5, 6, 7, 8, and 9. Since this interpretation is still in common use, a designation of a specific method of obtaining this result as three-point protection is somewhat confusing.

The results to date indicate that primary fuses may be expected to blow even though the protective device is connected ahead of the fuse link and presumably shunts the surge current around it. In my opinion this is due to (1) mechanical damage of the link; (2) short circuits attending storms; (3) surge currents flowing through the link together with associated secondary short circuits. Even though a protective device successfully shunts the major portion of the surge current around the fuse link, the charging current of the winding flows through the link. For steep front lightning surges this is by no means a negligible current and considering repetitive strokes the accumulative effect may be sufficient to blow the fuse link, particularly if the rating of the link is small. In addition to this effect, short circuits occur in the house wiring due to induced surges on the ungrounded secondary wires flashing over to grounded neutral. It is apparent that this condition cannot be eliminated and improvement in service can only be expected either by eliminating primary fuses or using large sizes.

C. F. Harding (Purdue University, Lafayette, Ind.): The principle and method of attack of this whole problem of protection of distribution systems may well be emphasized again. When first conceived the length of time and expense involved in its solution seemed prohibitive. One executive in the Middle West said it would take $50,000 and many years to get an answer to the interconnection problem if undertaken by statistical analysis of lightning discharges in natural thunderstorms in representative areas of several large cities.

As a predictive and foreshortened study, therefore, an experimental yet full-sized, four-span standard installation was made at Purdue University under the auspices of the Utilities Research Commission of Chicago whereupon thousands of induced surges were superimposed by means of a high-voltage laboratory surge generator. The results of these two years of testing of various types of interconnection and protection were reported at length in the AIEE Transactions, March 1932, and in Bulletin No. 42 of the Engineering Experiment Station of Purdue University.

Since the solid interconnection was definitely proved by these tests to be most effective and since no dangerous excessive voltages appeared on the consumers' premises *if adequately low-resistance grounds were provided thereon*, many companies were encouraged to install such interconnections at a very much earlier date than would have been possible by the statistical field-study method. These predictions of the best methods of protection are well substantiated by the conclusions of this paper. Reports, during recent years, of large reductions in transformer burnouts, and of no trouble from excess potentials at the consumers' premises, after the interconnection was made, are confirmed by this paper and the resulting discussion thereon.

This general procedure, therefore, seems to justify the practical results and warrant the further consideration of laboratory methods of attack as co-operative projects between university research staffs and public utility and manufacturing corporations in order that the probable best solutions to such problems may be secured more promptly and with minimum of expense.

It is encouraging to note the very large increase in such interconnections during the last few years as well as the tendency to ground transformer cases and to reduce ground resistances on rural consumer circuits. The success that these changes have attained is a further confirmation of the worth of such full-sized laboratory tests. However, the limited number of meter burnouts may not necessarily be a criterion for indicating the correspondingly small number of cases of high potential on the consumers' premises as some types of meters, at least, will withstand relatively high surge potentials without burnout or serious change of calibration, the potential coils having sufficiently high inductance and such design as to permit flashover and the current coils having sufficiently low inductance and high carrying capacity to avoid damage due to heavy surge currents therein. The laboratory tests previously mentioned indicated that other consumer apparatus would flashover or burn out before meters would be damaged and that with house circuits closed and lamps lighted the attenuation of such surges was a worth-while safety factor.

J. R. North (The Commonwealth and Southern Corporation, Jackson, Mich.): Mr. Smith's paper presents a very considerable number of operating records covering the experience of different companies with distribution transformer protection from lightning. The conclusions reached should be very interesting to distribution engineers and others concerned with the application of protective equipment.

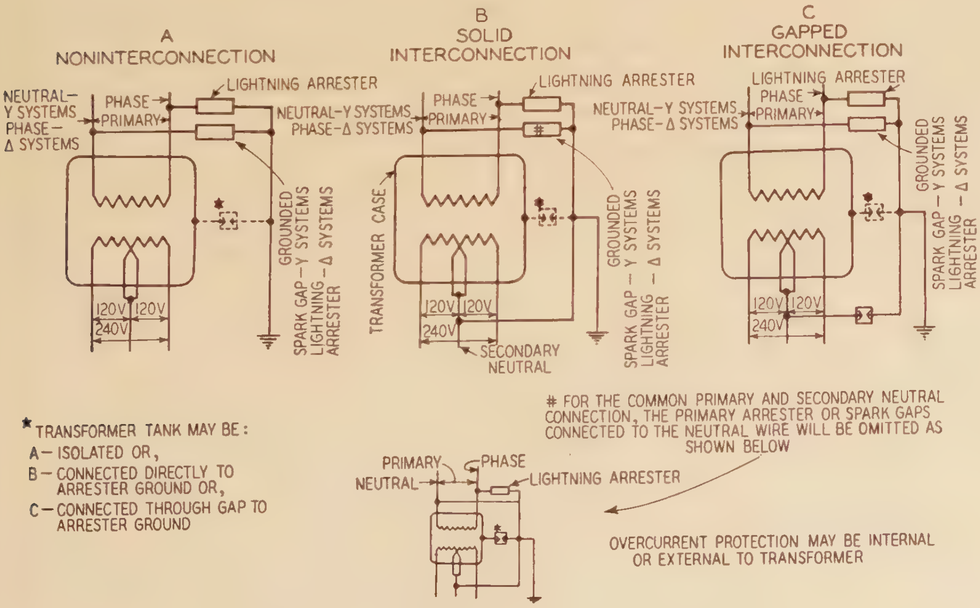
It would appear that the results of this study could be made more conclusive if it were possible to evaluate further the effects of:

(*a*). Number and severity of storms for the various locations.

(*b*). Age and relative insulation strength of the transformers involved.

(*c*). Relative protective characteristics of the lightning arresters.

The various methods of lightning protection of distribution transformers and the conclusions given are classified in the paper according to current terminology and by means of nine connection diagrams. As mentioned by Mr. Smith, it is difficult to compare the operating performance and the relative merits of the various schemes because of the lack of uniformity in nomenclature used throughout



* TRANSFORMER TANK MAY BE:
A – ISOLATED OR,
B – CONNECTED DIRECTLY TO ARRESTER GROUND OR,
C – CONNECTED THROUGH GAP TO ARRESTER GROUND

# FOR THE COMMON PRIMARY AND SECONDARY NEUTRAL CONNECTION, THE PRIMARY ARRESTER OR SPARK GAPS CONNECTED TO THE NEUTRAL WIRE WILL BE OMITTED AS SHOWN BELOW

OVERCURRENT PROTECTION MAY BE INTERNAL OR EXTERNAL TO TRANSFORMER

Figure 1. Distribution transformer protective schemes

the industry. Therefore, it would appear to be highly desirable to adopt a uniform and simple system of classification of the protective methods.

The lightning arrester subcommittee of the Institute's protective devices committee has given considerable thought to this, and figure 1 shows three diagrams illustrating all the connections commonly used for protecting distribution transformers. The three basic schemes of connections may be designated as (*A*) noninterconnection, (*B*) solid interconnection or (*C*) gapped interconnection, according to the connections of the ground leads of the primary protective devices and the secondary neutral. These leads may not be connected to the secondary neutral. They may be solidly connected or connected through a gap.

It will be seen from the notes on figure 1 that these three diagrams are applicable to all types of systems and schemes of connection. It is urged that some such uniform scheme of diagrams and terminology be adopted to avoid confusion and to eliminate lengthly descriptions of the various different protective schemes.

L. G. Smith: The suggestions made by Halperin, North, and Hodnette that the storm frequency for each year in each locality be weighted in determining the totalized data in the summary tables, might be misleading in that there is still another factor which cannot be determined, namely, storm severity. For example, on our own company system we have had years in which as many thunder storm days were experienced as in other years but the percentage troubles were materially lower due to variations in storm frequency. It is planned after five or six years' data have been obtained to weight the data supplied by each company by isoceraunic level for the territory for which the data was reported. Likewise the age and condition of the transformers involved should be considered as suggested by Andrews and North. However, in collecting data of this kind it is necessary not only to obtain from each company the numbers of transformers failing and number of primary fuses blown for each type of transformer but it is also necessary to know the number of transformers of each type on the system. If it was decided to obtain data in this amount of detail it is believed complete operating data would be obtained from only a few companies, as most companies do not keep their records in as much detail as would be required. It is believed that the obtaining of operating data on a large number of transformer installations will tend to average the effect of age and condition of transformers.

As Halperin suggests, the use of the solid interconnection is probably the best and cheapest means of lowering the ground resistance of the lightning arrester ground. Both Halperin and McMorris have discussed the effect of interconnection upon lightning arrester failures from two different points of view. While it is true as Halperin stated the effect of lowered ground resistance is to permit more surge current to pass through the arrester and hence probably result in more arrester failures, attention is called to the data in the McEachron and McMorris paper, which indicates that a very large percentage of the surges experienced on distribution systems are of lower current values than those which would cause arrester failures. It is also true that many failures of arresters even during storms may be due to other causes than high surge currents.

In reference to the poor performance of gapped interconnections as discussed by Halperin and Andrews it is quite possible that the voltage at which the gap breaks down is not materially different from the bushing flashover of the transformers protected. This is particularly true of the older types of transformers with smaller bushings. If such is the case it would be anticipated that the performance with the gapped interconnection would not be materially different from that with the standard connection in view of the fact that the flashover of the bushings results in effecting an interconnection with the secondary neutral. It is true as Andrews has mentioned that the rates of trouble are materially higher in rural districts. It is possible that the unexplained blowing of fuses mentioned by Andrews may be due to bushing flashovers or flashovers from the leads to the case that do not leave marks sufficiently to be distinguished by a subsequent inspection.

In reference to the relationship between the fusing schedule and the rate of primary fuses blown as discussed by Sanford, an attempt was made to correlate these two points in obtaining data. However, it is quite difficult to reduce a fusing schedule to a single statement. In summarizing the data an attempt was made to reduce all fusing schedules to a percentage basis. As Hodnette has suggested, from a theoretical standpoint at least the higher the fusing schedule the lower the probable rate of primary fuses blown.

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following five pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

The Rating of Resistance-Welding Transformers

Discussion and author's closure of a paper by C. E. Heitman published on pages 125–30 of this volume (March section) and presented for oral discussion at the electric welding session of the winter convention, New York, N. Y., January 26, 1938.

D. I. Bohn (Aluminum Company of America, Pittsburgh, Pa.): I am in hopes that Mr. Heitman's excellent paper on this subject will provoke quite vigorous comments, not only from those in the welding-machine industry, but from users and power companies.

In my opinion a welding machine should have a dual electrical rating. Part of this rating should be that of the transformer only. It is not so important as to just what method is used to rate this transformer as long as it is agreed on. The second part of the welding machine rating should advise the electrical conditions of the machine as a whole. A spot welder for instance may have a transformer of a 100-kva rating defined in whatever method is agreed on. The machine itself however may be of such a design as to require a demand of 225 kva. The same transformer in another machine of different design may require a maximum demand of only 150 kva. It is quite obvious therefore that to rate the machine on the basis of the transformer alone is misleading to all concerned.

Inasmuch as the thing that makes the weld is amperage, the maximum available amperes at the point of weld should be given as part of the machine rating.

If all machines have ratings of this nature, the question as to whether a machine will do a certain job could be answered directly without the necessity of making rather extensive electrical or welding tests as are necessary with the present systems of rating.

L. G. Levoy (General Electric Company, Schenectady, N. Y.): The author has presented a very lucid and timely exposition on the subject of resistance welding transformer rating. The widespread application of electronic control in the past few years has necessitated more dependable information to enable the user to select the proper control. Either overestimating or underestimating control requirements from the name-plate ratings may cause considerable unnecessary expense. In the past the only safe way to determine the requirements has been to make actual measurements on the transformer involved. This often entails delay and inconvenience, which can be avoided by proper name-plate designation.

The resistance welder manufacturers know these requirements. For a variety of reasons, they have not placed this information on the name plate. Probably the chief reason for the absence of this information is that the user, in many cases, does not know the secondary current requirements for welds, in which cases this information is useless. Now, however, many users know these requirements and yet from the data on a welding machine name plate cannot determine the suitability for jobs where the current requirements are known. Many manufacturers furnish this information on request and probably will welcome a new sane standard for name-plate designations to be followed by all manufacturers.

In order to eliminate all ambiguity and enable the user to determine whether or not his requirements are within name-plate rating of the transformer, it is necessary to specify, in addition to the items listed by the author, the maximum allowable time over which the duty cycle may be averaged with the understanding that this average is to be taken to include the most severe duty cycle imposed. This time is intimately associated with the thermal time constant of the transformer. The question arises whenever the duty cycle is irregular and the transformer is working near its rated capacity. Since this characteristic will vary with each size and design of transformer, the maximum allowable averaging time for the most severe duty cycle should be stated on the name plate to protect both the manufacturer and user against unintentional overloading.

The author discusses the use of an autotransformer or a tapped primary winding for varying the secondary current. There is another practical method known as phase control, which eliminates the necessity and expense of supplying either an autotransformer or a tapped-primary winding. It is accomplished, with electronic control, by delaying the start of the period of conduction of each voltage wave beyond the power-factor angle of the welder. This permits a smooth, stepless variation of heat over the entire range. Ease and speed of adjustment has made this method popular with operators where frequent changes in heat are required on work of varying nature, or where the steps of current adjustment by the available taps are too large.

L. W. Clark (The Detroit Edison Company, Detroit, Mich.): Mr. Heitman deserves the thanks of all concerned with the welding industry for his comprehensive discussion of the fundamentals involved in properly rating resistance welding transformers. There is bound to be some disagreement as to the details of standardization and recommended name-plate data, but the author's logical presentation should be a great help in crystallizing the ideas of various interested groups with a resulting standardization valuable to everyone.

From the standpoint of those interested in providing an adequate power supply for resistance welders, both in the plant itself where the welders are located and also from the power system providing the service, there are two factors mentioned by the author which may be further emphasized. He clearly shows the value of reduced impedance drop in the transformer but only mentions the effect of the impedance of the secondary circuit and states that it is this impedance that constitutes the load on the transformer. Only a very small percentage of the total secondary impedance is actually accounted for in the weld itself, the bulk of it being found in the conducting path from the transformer to the weld. I believe that, particularly in large machines, further emphasis should be placed upon the importance of keeping the secondary circuit as compact and of as low an impedance as possible thereby showing definite savings in welding transformer size, required distribution facilities throughout the plant, and power demands drawn from the power system.

It hardly seems necessary to discuss this point but it is a fact that many of the large present-day flash and projection welders have much higher reactive losses than necessary, resulting in oversized supply equipment all along the line. Money spent in improved design will be repaid many times over in savings in expenditures for transformer capacity and distribution facilities. The amount of current required to make a good weld is pretty much of a fixed quantity for a given job, but the type of path provided for conducting the current from the welding transformer to the work can be varied. Some of the welder manufacturers may not have realized the importance of this factor, and it is hoped that new machines will be of improved electrical design, resulting in lower power demands and lower costs of service for the user.

On the subject of name-plate rating, it is highly desirable that when the transformer is part of a complete welding machine, the maximum instantaneous kilovolt-ampere demand be given, as recommended by the author. With the present practice of a name-plate rating based on a 50-per-cent-duty cycle, there is no logical basis upon which to lay out an adequate supply system. It becomes necessary to "guess" that the instantaneous demand will be two to five times the name-plate rating which is certainly poor basic information upon which to authorize plant expenditures for serving new equipment. The maximum instantaneous demand with the transformer operating on the highest voltage tap should be incorporated as part of the standard name-plate data.

H. S. Hubbard (nonmember; General Electric Company, Pittsfield, Mass.): Mr. Heitman's paper is of timely interest to both the user and manufacturer of welding transformers. Certainly it is apparent that the subject of transformer ratings for this class of service should be given serious consideration and it is logical that this should follow other standard lines of equipment.

The 50-per-cent-duty cycle, so commonly used as a rating basis, has little bearing on the capability of a transformer to perform satisfactorily on duty cycles for other than which it was originally designed. While the theoretical equivalent rating for any other period of operation may be easily determined from this value, there are real practical limitations dependent upon the transformer characteristics, which may restrict the use of a particular unit for a specific application.

Above all, the manufacturer should know the maximum instantaneous load requirement and the maximum duty cycle at that load. This permits him to so proportion his design that reasonable values of resistance and reactance are obtained and to determine the thermal rating on an equivalent continuous basis.

It is desirable that reactance and resistance be considered separately rather than as combined impedance for the reason that with the low power factor in the usual type of welding circuit, the reactance component is more nearly in phase with the load current and consequently influences the regulation much more than the resistance component. Thus two similarly rated transformers having the same impedance value might vary considerably in the matter of regulation.

In specifying a definite impedance in per cent, it is assumed that the designer has full control over the governing factors. This is not always so and cases will arise where it is economically impractical to meet such requirements. Perhaps it would be best to state the impedance or reactance rather than limit it to a fixed value.

Two transformers of the same kilovolt-ampere rating, but with different secondary voltages might have the same impedance drop in volts, but in per cent would vary inversely with the actual voltage output. This it would seem, might penalize an ordinary satisfactory design, if limits are too closely restricted.

While the true ohmic value of the loop impedance is numerically low as stated in the paper, the per cent impedance is usually extremely high, approaching 100 per cent of the transformer voltage. The power component across the weld is a very small factor and the voltage rating of the transformer is consequently influenced largely by the inductance of welding circuit or loop. Thus it is of utmost importance that the voltage drop in any welding circuit be carefully determined before the kilovolt-ampere rating can be specified.

In the matter of temperature rise, would it not be consistent to limit this to the AIEE standards for whichever class of insulation is used in the transformer design, that is, for class *A*, 55 degrees centigrade; and for class *B*, 75 degrees centigrade.

In connection with the chairman's request for items which might profitably be studied by the committee, I would like to suggest that an effort be made to correlate existing data on "loop" inductance and the methods used to calculate this circuit. There appears to be a divergence of opinion in this regard and it is difficult to obtain consistent data which might be applied generally. This is particularly important for as mentioned earlier in this discussion, the voltage drop in the secondary circuit is the major determining factor in the selection of the proper transformer voltage and hence the kilovolt-ampere rating for a particular job.

Some time ago in co-operation with one of the equipment manufacturers, we made a brief study of the kilovolt-ampere requirements for various size loops and based on the data submitted, developed a simple family of graphs. Although largely empirical, we have found these curves quite useful as a reference and I am sure that a more thorough study of this particular problem would be generally helpful to the industry.

S. M. Humphrey (nonmember; Taylor-Winfield Corporation, Warren, Ohio): I do not believe that anything will be accomplished unless the AIEE can agree to adopt a standard method of rating which has a reasonable chance of being accepted by other organizations such as the manufacturers of resistance-welding equipment, and their customers. Fundamentally it does not make any particular difference what the system of rating is as long as it is based on sound engineering principles and is universally acceptable.

Since a very large percentage of purchasers and users of resistance welding equipment are not electrical engineers, in fact they are not conversant with electrical terms, but have been brought up to consider that a transformer with certain kilovolt-ampere name plate will stand about so much, it would not be at all practical to attempt at this time to suddenly change this name-plate figure and then attempt to explain that a 70-kva transformer is now the same as a 100-kva used to be.

For this reason I strongly recommend that the present system of rating based on a 50-per cent duty cycle be adopted as standard by the AIEE. This would be as equally understandable by electrical engineers as the 100-per cent duty cycle and in the eyes of many users would not constitute any change at all.

In order to completely specify the transformer, it seems to me it would also be worth while to specify what its rating should be on the low tap as well as the high tap.

In regards to per cent impedance, I believe the best system would be to actually specify the impedance on the name plate in all cases. I am not in favor of specifying both resistance and reactance since in most cases the impedance is sufficiently close for all practical calculations and, furthermore, the actual resistance is a small part of the impedance and also very difficult to measure without machining special short-circuiting members for that purpose.

In regard to the temperature rise, I believe it best to adopt the present standard of 55 degrees for class-*A* insulation, and 75 degrees to class-*B* insulation.

Regarding the cooling water required, it might also be worth while to specify what pressure is needed to obtain the required gallons per minute for cooling.

In regard to the machines, it is very difficult to specify on the machine name plate the maximum primary current which will be drawn. If this were done it would have to be specified with the lower knee in its raised position and with the shortest horns which the machine could use, and if this figure were then used as a basis for power installation and purchase of control equipment, it might burden the purchaser with a much more expensive installation than was required for the work to be done.

At the present moment the Taylor-Winfield Corporation are supplying with a portion of their standard machines complete curves covering both the primary and secondary currents for all possible geometrical combinations of the secondary circuit and will extend this service to cover their entire line of machines as soon as possible.

The use of electronic control has been mentioned here by one of the representatives of the General Electric Company. There is one fact regarding its use which I believe should be pointed out since it will have some bearing on the power company's problem, and that is that heat reduction by means of electronic control results in a higher root-mean-square primary current than is obtained if the current reduction is made by means of a tap transformer or autotransformer. The increase in root-mean-square value is accounted for entirely by harmonics due to the wave form obtained from electronic heat control. The fundamental component of the current is the same with either system on secondary current reduction.

The above comments should not be construed to mean that I am opposed to electronic control. I believe it to be a very valuable addition to resistance welding equipment and from actual use have found it to be as fine a means of welding-current control as has yet been devised.

G. S. Bernard (nonmember; Aluminum Company of America, Pittsburgh, Pa.): I certainly agree with Mr. Heitman in that the name-plate data now furnished on resistance-welding transformers is of little value to the user of this equipment. The use of a thermal equivalent continuous kilovolt-ampere rating based on the maximum continuous secondary current which can be drawn from the transformer without exceeding the safe operating temperature of the insulation materials employed and the maximum rated open-circuit voltage is a logical method of rating any transformer whether for continuous or intermittent duty.

In making use of this kilovolt-ampere rating as proposed by Mr. Heitman, we must not lose sight of the fact that the current delivered by the transformer and not the kilovolt-amperes delivered should be used as a basis to determine if any given loading is within the safe limits for a given transformer.

Thus, regardless of the secondary voltage which may be used to obtain the welding current, the thermal equivalent continuous kilovolt-amperes is obtained by multiplying the secondary current by the maximum rated open circuit secondary voltage and the square root of the duty cycle.

As an example, consider the 34.7-kilovolt-ampere transformer proposed by Mr. Heitman.

Suppose that we wish to find the maximum duty cycle at which each of the following welding loads could be supplied.

Case I

Welding current = 10,000 amperes
Load impedance = 0.001 ohm

Case II

Welding current = 10,000 amperes
Load impedance = 0.0005 ohm

Case III

Welding current = 5,000 amperes
Load impedance = 0.001 ohm

Case I

Open-circuit voltage required is:

$$V_1 = 10{,}000 \times 0.001 + 0.04 \times \frac{10{,}000}{3{,}000} \times 11.6 = 11.6 \text{ volts}$$

$$\frac{10{,}000 \times 11.6}{1{,}000} \times \sqrt{D_1} = 34.7 \text{ kva}$$

$$\sqrt{D_1} = 0.30,\ D_1 = 0.09 = 9.0 \text{ per cent}$$

Case II

Open-circuit voltage required is:
$V_2 = 10{,}000 \times 0.0005 + 0.04 \times 10{,}000 \times 11.6 = 6.6$ volts.
But in calculating thermal equivalent continuous kilovolt-amperes we use the rated voltage

$$\frac{10{,}000 \times 11.6}{1{,}000} \times \sqrt{D_2} = 34.7 \text{ kva}$$

$$\sqrt{D_2} = 0.30,\ D_2 = 0.09 = 9.0 \text{ per cent}$$

Case III

Open-circuit voltage required is:

$$V_3 = 5{,}000 \times 0.001 + 0.04 \times \frac{5{,}000}{3{,}000} \times 11.6 = 5.8 \text{ volts}$$

Again we use the rated secondary voltage

$$\frac{5{,}000 \times 11.6}{1{,}000} \times \sqrt{D_3} = 34.7 \text{ kva}$$

$$\sqrt{D_3} = 0.60,\ D_3 = 0.36 = 36 \text{ per cent}$$

The above calculations show the method of using the T.E.C. [thermally equivalent continuous] kilovolt-amperes in calculating safe loadings for welding transformers. Had we used the actual secondary voltage instead of the rated maximum voltage, we would have obtained duty cycles of 27 per cent for case II and 143 per cent for case III which, considering the currents used, are obviously incorrect.

In selecting the proper maximum open circuit secondary voltage to obtain a given secondary current, an allowance for voltage drop in the lines supplying the welder transformer must be made. Unless the welder happens to be located favorably with relation to a large source of power, it will not be economical to provide a voltage regulation better than 2 per cent based on the T.E.C. kilovolt-ampere rating or six per cent based on the maximum current demand during the weld. As this supply line impedance is comparable to the transformer impedance, it should be included in the calculations of open circuit secondary volts required.

The inclusion of this factor will indicate the use of open circuit voltages some six to ten per cent higher than those which would be used if only transformer and load impedance were considered. The transformer kilovolt-amperes required will also have to be increased in proportion to the increased secondary voltage.

F. H. Roby (Square D Company, Milwaukee, Wis.): Manufacturers and users of resistance welding control equipment welcome any standardization of the kind suggested in Mr. Heitman's paper entitled, "The Rating of Resistance Welding Transformers."

Although welding transformers presumably have heretofore been rated on a 50-per-cent-duty-cycle basis, it has been almost impossible to calculate the magnetic contactor load in amperes, because of widely varying transformer design. Contactor ratings are properly based upon the load current (primary of transformer), primary voltage, interruptions per unit of time and length of welding period. Of the four factors involved, the load current is the most important and least often determinable.

It is true that nearly all manufacturers of control equipment have conducted tests to fix values of currents that can be safely interrupted under given operating conditions but this data is useful only to the individual in possession of the transformer or welding machine performance characteristics. If sufficient information is not included as name-plate data on both transformers and machines, there is little hope that contactors will be successfully applied by any one except the manufacturer of the equipment.

If the standardization under discussion becomes effective and all concerned use it, then manufacturers of control equipment can publish contactor-rating data that will be helpful to all in the industry.

R. L. Briggs (nonmember; Thomson-Gibb Electric Welding Company, Lynn, Mass.): I agree in principle with the recommendations suggested in this paper. It should be possible for a user of resistance-welding equipment to determine the exact capabilities of his machine. He should know how much it is capable of doing and how rapidly it can be used. I should like, however, to take certain exceptions to his recommendations and statements.

In a great majority of cases finished machines never experience

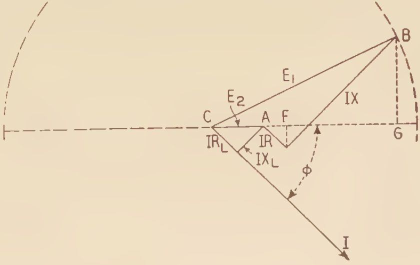


Figure 1

any changing of their transformers, portable spot welding equipment being practically the only exception. I therefore recommend that the complete welder be rated with the exception that the short-circuit impedance of the complete welder be stated rather than the per cent impedance at rated kilovolt-amperes. I also recommend that the method of rating suggested in this paper be applied to all transformers installed or to be used with portable welding equipment, with the exception that the six-per-cent value assigned as a standard for the percentage impedance be altered.

The value of six per cent suggested as a standard for the impedance drop does not seem consistent with the actual conditions involved in a resistance welding transformer. Consider figure 1 which shows the load vector diagram of a transformer referred to the secondary. Now

E_1 = open-circuit secondary voltage
E_2 = secondary voltage across load
I = load current
R_L = load resistance
X_L = load reactance
R = transformer resistance
X = transformer reactance
ϕ = current phase angle

By the definition of the impedance drop

$$Z_d = \frac{E_1 - E_2}{E_1} = \frac{\overline{AH}}{E_1} \tag{1}$$

But

$$\overline{AH} = \overline{AF} + \overline{FG} + \overline{GH} \tag{2}$$

$$\overline{AF} = IR \cos \phi \tag{3}$$

$$\overline{FG} = IX \sin \phi \tag{4}$$

The value of $\overline{GH}$ in a transformer is small in proportion to $\overline{AH}$ and this is true for all loads except at or near no load and for any power factor. Let us assume that $\overline{GH} = 0.2\overline{AH}$ as a maximum and use this value in our analysis.
Therefore

$$\overline{AH} - 0.2\overline{AH} = IR \cos \phi + IX \sin \phi \tag{5}$$

$$\overline{AH} = 1.25\,(IR \cos \phi + IX \sin \phi) \tag{6}$$

Now

$$Z_d = \frac{\overline{AH}}{E_1} = \frac{1.25}{E_1}(IR \cos \phi + IX \sin \phi)$$

$$= 1.25\frac{I}{E_1}(R \cos \phi + X \sin \phi) \tag{7}$$

But

$$\frac{E_1}{I} = Z_t \text{ the total impedance} \tag{8}$$

Hence

$$Z_d = \frac{1.25}{Z_t}(R \cos \phi + X \sin \phi) \tag{9}$$

Equation 9 should be substantially accurate for the thermally equivalent kilovolt-ampere load condition, and at this loading it has been suggested that $Z_d = 0.06$. Therefore

$$0.06 = \frac{1.25}{Z_t}(R \cos \phi + X \sin \phi) \tag{10}$$

or

$$0.048Z_t = R \cos \phi + X \sin \phi \tag{11}$$

This last equation states a relationship between the total impedance and the transformer resistance and reactance. If the transformer design and load conditions result in a very high power factor load, then

$$0.048Z_t = R \text{ approximately} \tag{12}$$

This is a condition closely met in actual practice and demonstrates that the $Z_d = 6$ per cent is a proper value for high-power-factor loads used with power transformers. If the transformer is a resistance-welding transformer and the loads are those met in resistance welding the power factor is low, and

$$0.048Z_t = 0.7R + 0.7X \text{ as an example} \tag{13}$$

This is a condition almost impossible to meet in actual practice. Actually the sum of the fractions of the transformer resistance and reactance in the case of butt welders may be $0.5Z_t$ which indicates that Z_d should approximately be 65 per cent for these types of welders. This value of Z_d must necessarily be different for the transformers used in the other types of welding machinery.

I therefore recommend that a value of Z_d be established for the welding transformer which is commensurate with the type of welder in which the transformer is to be installed. It is still my belief, however, that excepting the portable welding equipment it is better to use the short-circuit impedance data for the purpose of rating the welder complete rather than to rate the transformer proper in terms of its impedance drop at a specified loading.

C. E. Heitman: It is gratifying to the author to note the number of very pertinent discussions of this paper which indicate that there is considerable interest in, and desire for, standardization of welding transformer ratings. It is sincerely hoped that this paper and these discussions will stimulate further activity in this direction which will bear fruitful results.

The discussion by Mr. Bernard brings out two important points which I failed to stress in the paper. First, that in calculating the maximum permissible duty cycle, the maximum open-circuit secondary voltage should be used in conjunction with the thermally equivalent continuous kilovolt-amperes. However in this connection I should like to bring out one more point which some of you may have considered already. Referring to case II of Mr. Bernard's discussion, with an open-circuit voltage of 6.6 volts, the member of primary turns will be roughly twice that used in obtaining the maximum secondary voltage. The primary resistance will therefore be approximately twice, but for the same secondary current, 10,000 amperes, the primary current will be one-half. The primary heating will therefore be $(I/2)^2 \times 2R = {}^1/_2\, I^2R$ or one-half its previous value.

The secondary heating will of course be the same. The determination as to whether or not the transformer can stand a duty cycle higher than nine per cent will depend upon what percentage of the total copper loss is contributed by the primary winding. If the primary could contribute all the copper loss it is obvious that the duty cycle could be doubled in this case, since the core loss, per weld, is approximately one-fourth its previous value. However, since the present design tendency is to make the primary copper loss low, a reduction of 50 per cent in this factor will make very little difference in the total copper loss. However for most present-day designs, the duty cycle could be increased above nine per cent in case II, but for safety it is not desirable to do so. If the actual values of primary and secondary copper losses are known, an accurate determination of the maximum permissible duty cycle (somewhat above nine per cent) could be made.

Second, Mr. Bernard brings out the point that the impedance of the primary line feeding the transformer should be considered in calculating the open-circuit secondary voltage of the transformers.

Both of these considerations were omitted from my paper since I felt that they might be confusing in a discussion of transformer ratings. I furthermore felt that although the question of primary feeder impedance is very pertinent to resistance welding, it was not within the scope of this paper. It is a subject within itself and one which needs further discussion.

Regarding the question raised as to the maximum allowable time over which the duty cycle may be averaged, I feel that this can best be answered by the manufacturers. I am therefore suggesting that they offer recommendations in this connection, with the idea in mind that this information will not be included on the name plate, but that values of time, depending upon the rating, or group of ratings, be given in the standards. For example, in transformers rated from 25 to 75 kva the duty cycle may be averaged over a certain period, whereas transformers rated from 75 to 150 kva may be averaged over a different time period. I recommend that the ratings be divided into such groups and a definite averaging time be assigned to each group and included in the standards, rather than adding this information to the name plate.

Mr. Hubbard's suggestion that the reactance and resistance be considered separately rather than as a combined impedance, is very pertinent. Such information would undoubtedly be desirable, if the manufacturers would agree to supply it. However, I feel that it is not essential. That a standard based on the assumption that the transformer impedance voltage is in phase with the load voltage, will take care of the worst condition, from a standpoint of regulation, and will therefore serve the purpose. If certain manufacturers desire to include this information on the name plate, or submit it to the customer in the form of a test report, I do not have any objections. However, in outlining standards such as these, I feel that the required name-plate information should be held to a minimum.

I am in hearty agreement with Mr. Hubbard's suggestion that the resistance welding committee make a study of existing data on loop impedances and methods used for calculating this data. I have certain data on this subject and I am sure many others connected with the art have likewise. A correlation of this data would prove most useful and beneficial to all concerned.

I am in partial agreement with Mr. Humphrey in that it does not make any appreciable difference what standard of rating is adopted, so long as it is technically sound and rigidly adhered to by the various manufacturers. From a technical standpoint, a rating based on a 50-per cent duty cycle is just as sound as one based on the continuous or 100-per cent duty cycle. I feel that the 100-per cent duty cycle rating is the most logical and I have recommended this for adoption as standard. However, if it is felt by all concerned that a standard rating based on a 50-per-cent-duty cycle will be more universally accepted and adhered to, I feel that this should be adopted.

In this connection I might add that in the discussion which followed the presentation of this paper, the suggestion was made that a standard be adopted which would keep the name-plate kilovolt-amperes as low as possible. Such a standard would obviously be based on a 100-per cent duty cycle. Rated on this basis a certain transformer might have a name-plate rating of 100 kva, whereas the same transformer if rated on the basis of a 50-per-cent duty cycle would have a name-plate rating of 141 kva.

I would like to express my further approval of Mr. Humphrey's suggestion that the required cooling be expressed in terms of water pressure required rather than in gallons per minute.

The thought expressed in Mr. Brigg's discussion has been mentioned before in certain verbal discussions which I have had with various interested parties. Mr. Briggs feels that it is not practical to obtain a transformer impedance as low as six per cent in units having a very low open-circuit secondary voltage. In the example he cites of a butt-welding transformer, the maximum open-circuit secondary voltage would be in the neighborhood of five volts. A normal impedance of six per cent would mean an impedance voltage drop of only 0.3 volts in the transformer. This, Mr. Briggs feels, is impractical to obtain. I think it best to abide by the advice and opinions of the various manufacturers in this matter, since through their experience, they are in a better position to state what they can obtain economically. I do know however that an impedance of six per cent can be obtained with an open-circuit secondary voltage of 15 volts in ratings up to 200 kva. To outline a group of standard impedances based on a kilovolt-ampere rating and open-circuit secondary voltage ranges might be too complicated for the purpose of standardization. It therefore seems desirable to omit from the standards any specification as to the quantitative value of the transformer impedance, but rather to require that the manufacturer state on the name plate, the value of the impedance, whatever it might be, at rated load. It will therefore be left to the judgment of the user to select the transformer having the lowest impedances, all other factors being equal.

Most of these discussions have been confined to items 5, 6, and 8 of my recommendations, and from them I am prompted to make the following changes in the recommendations:

Item 6 to read "Per cent impedance at rated kilovolt-amperes"

Item 8 to read "Type of cooling required (if water-cooled state required pressure at specified intake temperature)"

I will not revise item 5 at present, but if it is mutually agreed that a rating based on a 50-per-cent-duty cycle will be more satisfactory to all concerned, I will co-operate toward its adoption as standard.

In conclusion I should like to emphasize the fact that these standards, in order to be effective, must first of all be technically sound, and secondly universally accepted by all concerned. It is sincerely hoped that the manufacturers and the users of welding equipment will co-operate toward arriving at a standard that will meet these two conditions.

Recent Advances in Resistance Welding

Discussion and closure of a report of the subcommittee on resistance welding of the AIEE committee on electric welding published on pages 37–8 of this volume (January section) and presented for oral discussion at the electric welding session of the winter convention, New York, N. Y., January 26, 1938.

L. W. Clark (The Detroit Edison Company, Detroit, Mich.): The report mentions the increased use of large-size welders, with transformer ratings in excess of 1,000 kva not being uncommon. Where there are many such large welders in a single plant as is true in most automobile and accessory plants, the problem of providing an adequate plant distribution system for serving the welders becomes important. The system must allow only a minimum of voltage drop which means a low-reactance design capable of serving the extremely high-current, low-power-factor loads.

A low reactance bus system designed and installed during the past year by one such user of welders is a distinct advance along such lines and a short description would seem appropriate. The main section of bus consists of a four-inch standard copper tube surrounding an extra-heavy three-inch copper tube with "micarta" tubing insulation between. The outer conductor is grounded, doing away with the necessity for any bus supports or outer insulation. Taps are brought out from the inner conducting tube at six-foot intervals, at which point a maximum of four welder control contactors can be located. Branch busses, each consisting of a two-inch standard tube surrounding a one-and-one-quarter-inch extra-heavy tube, radiate from the main bus at intervals throughout the plant.

The main bus can transmit 1,000 amperes of 40-per-cent-power-factor 440-volt welding current, a distance of 800 feet with only one-per-cent voltage drop, and the branches can transmit the same current 300 feet with one-per-cent drop. Large welders with current swings of 3,000 and 4,000 amperes can thus be served at considerable distances from the supply transformers and not cause over three- or four-per cent voltage drop in the bus system.

One such bus system, fed by 1,500 kva of transformers, serves four floors of factory area with a maximum transmission distance to the furthest machine of about 300 feet. Another is laid out in the form of a loop with over 1,000 feet of bus for serving a large ground floor manufacturing space. There are a total of about 18,000 kva of various types and sizes of resistance welders operating in regular production from these two systems.

C. L. Pfeiffer: I wish to thank Mr. Clark for his description of a low-reactance bus system for large-capacity resistance-welding machines. The question of power supply has always been not only an important but a vexing one in resistance welding for both the user and power company and improvements along these lines are of vital interest to the industry.

An Electronic Arc-Length Monitor

Discussion and author's closure of a paper by Walther Richter published on pages 115–17 of this volume (March section) and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 25, 1938.

J. E. Waugh (nonmember; General Electric Company, Schenectady, N. Y.): This discussion covers merely the scope of an "Electronic Arc-Length Monitor" and not the equipment involved.

A layman is very apt to infer that, if the monitor is set within proper limits for a given electrode and the arc length is maintained within these limits by the welding operator, the result will be a perfect weld. This would mean that at last the boiler code authorities had found an instrument to check the quality of the welds.

However, it is not necessarily true that good welds will be produced if the operator maintains an arc length within the monitor limits. It is possible to obtain correct arc-length indications from the monitor and still obtain a very unsatisfactory weld. Conversely, it is possible to obtain very erratic results with an arc length monitor and still produce a satisfactory weld-metal deposit.

Under the first condition, one of the chief causes of weld defects is the failure on the part of the operator or automatic welding equipment to obtain proper fusion to the side walls of the joint being welded. The arc-length monitor will not indicate such a condition, since the operator can hold the correct arc length and still not direct the arc sufficiently against the side walls to obtain proper fusion.

In the second case, in making the first pass of a vertical fillet or butt weld, the operator must "whip" his electrode in and out of the molten pool in order to properly locate the weld metal. This condition will show very erratic indications on the monitor, yet the weld is perfectly sound.

Both of these conditions are very clearly shown on a recording voltmeter which we have used with the same purpose in mind as the monitor, namely, to predict the quality of the weld. An examination of many charts and the result of the physical tests forced us to reach the conclusion that we could not predict the quality of the weld from the chart readings.

From our point of view a monitor of the type described in Mr. Richter's paper would prove useful in training new men as welders, indicating to the man the correct voltage he should be maintaining. It should also prove valuable as an occasional check on production welders, but we feel that its general use, while acting as an aid toward improving the quality of the weld, could not represent a "cure-all" for weld defects.

Walther Richter: The instrument was never intended to predict the quality of the weld, since we know of course, that the arc voltage is only one factor of many affecting the quality of the weld. We therefore fully agree with Mr. Waugh that the use of the instrument cannot guarantee a perfect weld. But on the other hand, it is well known that various electrodes require different voltages for best results and it is clear that if the welder fails to use the proper voltage, an inferior weld will certainly be obtained. The instrument will in this case eliminate at least the possibility of a bad weld due to using the improper voltage, and therefore seems to render a worthwhile service. We feel that the instrument has great value in training men, checking up on their performance and in all cases where it is desirable or necessary to hold the arc voltage within close limits.

Transactions

Papers and Discussions Comprising Pages 227–294 of the 1938 Volume

A Carrier Telephone System for Toll Cables

By C. W. GREEN
MEMBER AIEE

E. I. GREEN
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Synopsis: A new 12-channel carrier telephone system for existing cables is described. This system, which incorporates a number of interesting departures from the previous carrier art, is now being manufactured in considerable quantities to meet increased traffic requirements.

AN IMPORTANT advance in the art of carrier telephony has been made by the development of a new 12-channel system, known as the type *K*, for toll telephone cables of existing type. It is applicable both to cables installed underground, and also to aerial cables, for which the wide range of temperature variation introduces quite difficult transmission problems. Field trials on cables previously installed between Toledo and South Bend have been successful, and the system is now being manufactured to meet field demands.

This new development is an outgrowth of the experiments at Morristown, N. J., described by Messrs. Clark and Kendall before this Institute in 1933,[1] and the essential principles of the new system were included in those experiments. The earlier work dealt, however, with cable specially designed for carrier operation, and only underground cable was experimented with. As that work drew to a close, it became clearer that because of general economic conditions several years would elapse before the Bell System would require any substantial increase in toll facilities. Hence this early system was not put into commercial form, but work was continued to determine the extent to which carrier could be applied to existing cables, of which more than 15,000 miles were available for such use. Serious problems of crosstalk at high frequencies had to be reckoned with. A more serious problem, however, was that of maintaining stability of transmission, since with aerial cable, which comprises about two-thirds of the existing cable mileage, the total variation in attenuation, due to temperature variation, is about three times that for underground cable, and the rate of variation not infrequently is several hundred times as great.

In spite of these and other difficulties, the capabilities of the present system go far beyond those of previous systems. As a development objective the maximum length was taken as 4,000 miles, with as many as five separate systems linked together. On the basis of results thus far obtained it is expected that for these exacting conditions the performance with respect to crosstalk, noise, transmission stability, width of voice band, and other characteristics will equal or exceed that of previous facilities for much shorter distances.

Superior performance has been achieved without material effect on the cost of the system. For distances of a few hundred miles, on moderately heavy traffic routes, it will provide telephone circuits at a much lower cost than previous facilities. The minimum distance for which the system will be useful may be less than 100 miles.

Interesting features of the new system are:

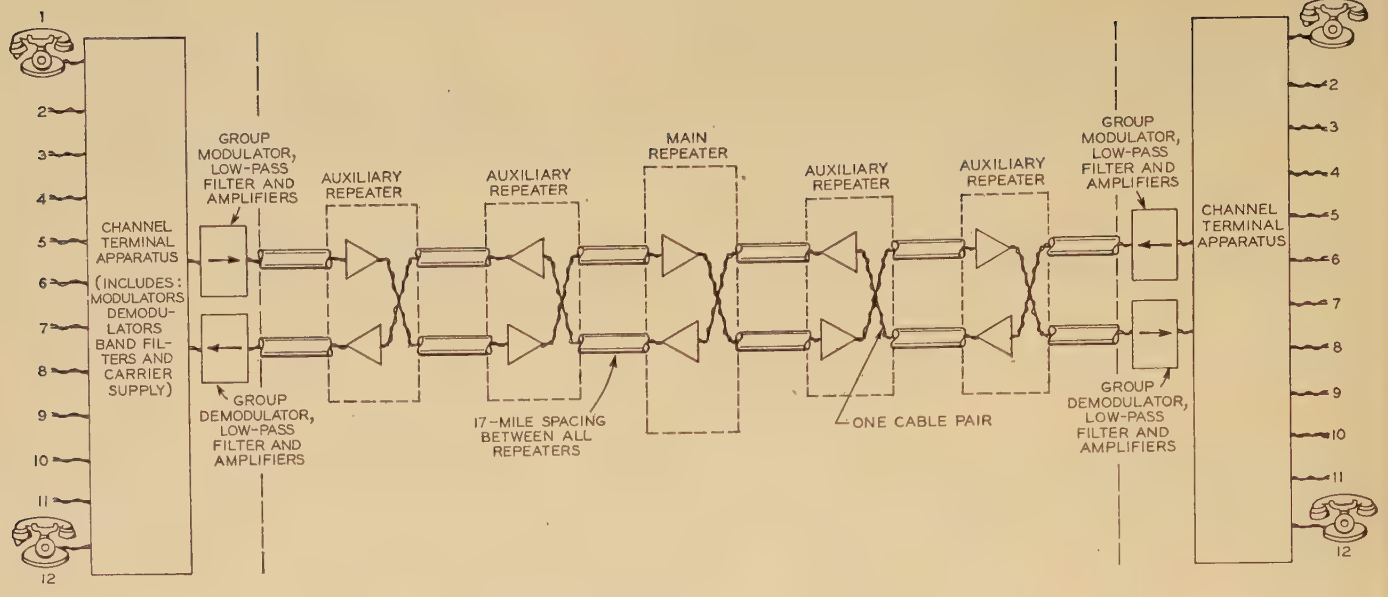
1. A line of very high attenuation, requiring high-gain repeaters spaced at approximately 17-mile intervals. This would mean, for the maximum distance for which the system is designed, more than 200 repeaters in tandem.
2. The use in the repeaters of the negative feedback principle of amplification to obtain the requisite stability and freedom from modulation.
3. Small auxiliary repeater stations, established between existing voice-frequency repeater stations, housing equipment which can be left for considerable periods of time without attention.
4. A system of transmission regulation whereby huge variations of attenuation, differing at each frequency, are automatically equalized to a high degree of accuracy.
5. New methods of crosstalk and noise reduction. Small adjustable mutual inductance coils are connected between carrier pairs to balance out the crosstalk. The noise is kept at an extremely low level to permit the high gains.
6. Channel terminal equipment designed so that it may be used in other types of carrier systems, thus simplifying development and manufacture, and facilitating the interconnection of different types of systems.
7. Speech bands considerably wider than those of existing facilities. The increase is obtained by spacing the channels at uniform 4,000-cycle intervals, and employing channel band filters containing quartz-crystal elements.
8. High speed transmission, which is of considerable value from the standpoint of minimizing delays and echoes.

A general description of the system is presented herein, and the different parts are taken up in greater detail in other papers.

Paper number 37-136, recommended by the AIEE committee on communication, and presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted October 29, 1937; made available for preprinting December 18, 1937.

C. W. GREEN is carrier telephone engineer with the Bell Telephone Laboratories, Inc., New York, N. Y., and E. I. GREEN is in the transmission development department of the same company.

[1] For all numbered references, see list at end of paper.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CHANNEL TERMINAL APPARATUS (INCLUDES: MODULATORS DEMODULATORS BAND FILTERS AND CARRIER SUPPLY)
GROUP MODULATOR, LOW-PASS FILTER AND AMPLIFIERS
GROUP DEMODULATOR, LOW-PASS FILTER AND AMPLIFIERS
AUXILIARY REPEATER
AUXILIARY REPEATER
MAIN REPEATER
AUXILIARY REPEATER
AUXILIARY REPEATER
17-MILE SPACING BETWEEN ALL REPEATERS
ONE CABLE PAIR
GROUP MODULATOR, LOW-PASS FILTER AND AMPLIFIERS
GROUP DEMODULATOR, LOW-PASS FILTER AND AMPLIFIERS
CHANNEL TERMINAL APPARATUS

Figure 1. Schematic of type K system

General Considerations

The type *K* system, whose elements are illustrated schematically in figure 1, operates on a "four-wire" basis, using the same frequency range, but different electrical paths, for opposite directions of transmission. Thus it differs from open-wire carrier systems, for which the line is not suitable for four-wire operation, and which therefore require complicated and expensive filters to separate the different frequency bands used for transmission in opposite directions. A high degree of shielding between the two cable paths is necessary to avoid the effects of near-end crosstalk, which would be serious because of the large level differences existing at the repeaters and the terminals. On routes where two or more cables exist, such shielding is obtained by employing two separate cables, with transmission in one direction only in each section of cable. On single cable routes, a similar arrangement is obtained by adding a small cable. Where there is no cable, two small cables may be provided. Also satisfactory shielding between the carrier pairs used for opposite directions of transmission has been obtained in short experimental lengths of cable by the use of a layer shield.

Frequency Allocation

In contrast to the original Morristown system which gave nine one-way channels per pair in the range from 4 to 40 kilocycles, the type *K* system has 12 channels in the range from 12 to 60 kilocycles. As shown in figure 2, the frequency range of the type *K* system is roughly

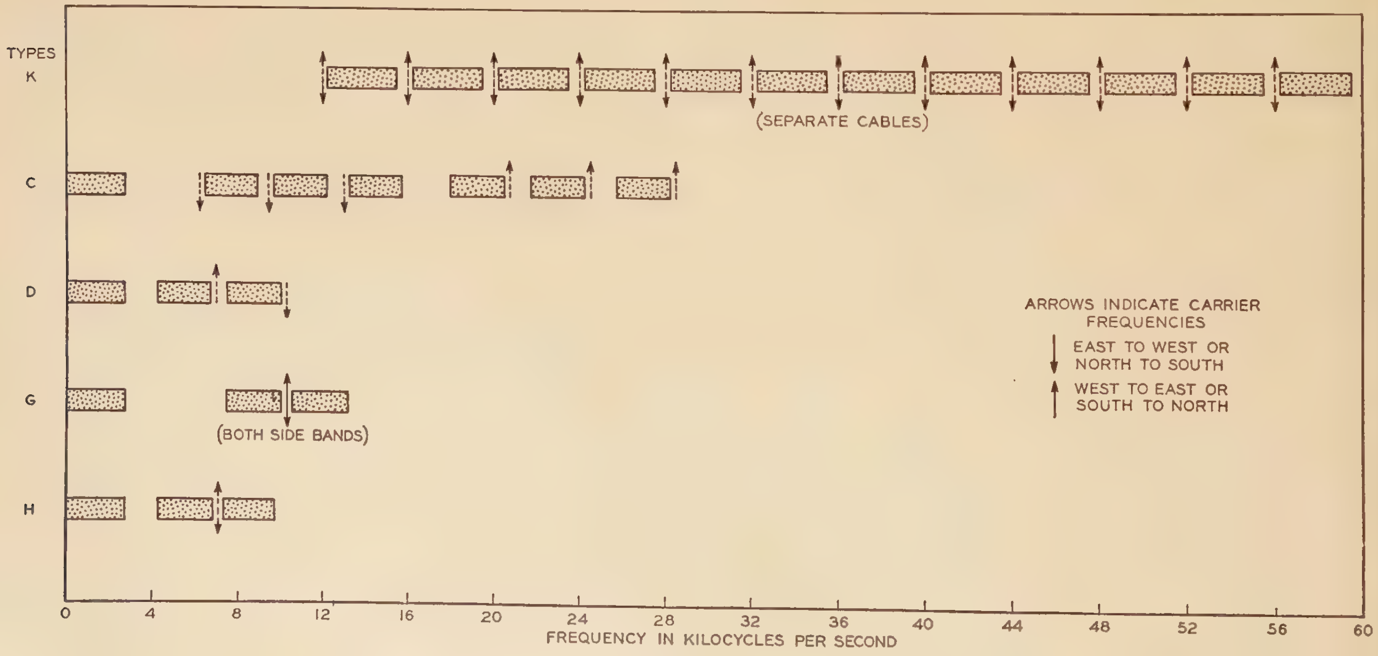

Figure 2. Frequency allocation of carrier telephone systems

double that of preceding open-wire carrier systems.[2] The choice of 12 and 60 kilocycles, respectively, as the lower and upper frequency limits was governed by economic considerations, and there is nothing technically insurmountable either in going to considerably higher frequencies or in utilizing the lower frequency range, which is now idle except for the use of the d-c path for purposes of transmission regulation and fault location. Important factors influencing the selection of the upper frequency are the crosstalk, which depends on the number of pairs utilized for carrier in one cable and the extent to which special crosstalk balancing means are used, and the attenuation, which largely controls the spacing between repeaters. Factors affecting the lower limit include the difficulty of maintaining accurate transmission regulation over the whole frequency range, and the design of the repeater, which becomes harder as the ratio of maximum to minimum transmitted frequency is increased.

The frequency range between 12 and 60 kilocycles accommodates 12 speech channels, each occupying a gross band of four kilocycles. The single-sideband method of transmission is employed, with carrier frequencies suppressed. The choice of a group comprising 12 channels was influenced not alone by the requirements of the type *K* system itself but also by those of other broad-band systems. From the earliest stages of the broad-band development it was recognized that there would be considerable advantage from the standpoints of flexibility of interconnection, of minimum development effort, and of large scale production of equipment units, if the designs of different broad-band systems could be so co-ordinated as to enable the same design of channel terminal equipment to be employed for each. A common 12-channel terminal unit developed for this purpose is used in the type *K* system.

The spacing of the channels in broad-band systems is important from the standpoint of the channel selecting circuits and the width of the derived voice circuit. As discussed in a recent article, a uniform 4,000-cycle interval has been adopted for the different channels of all broad-band systems.[3] The speech band width obtained with this spacing is in keeping with recent improvements in telephone instruments and other parts of the telephone plant. Over-all transmission-frequency characteristics for a single link and a five-link connection are shown in figure 3.

Cable Attenuation

The type *K* system is designed to be applied to the number 19 American Wire Gauge (0.9 millimeter) pairs commonly found in existing cables. (The Morristown system used 16-gauge pairs.) Because the conductors are small and closely spaced, with paper and air dielectric, the attenuation of a nonloaded 19-gauge pair at the frequencies involved is inherently high, as will be seen from figure 4. Because of the high attenuation, the repeaters must be placed much closer together than is necessary for voice-frequency cable circuits. Fortunately this effect is partly offset by the fact that it is possible, as discussed later, to use higher gains in the carrier repeaters.

The cable pairs exhibit the rise in attenuation with frequency which is familiar in most transmission circuits. This effect is brought about largely by the increase in conductor resistance, due to skin effect, and the increasing dielectric losses. More important than this, however, is the fact that the resistance of the wires and the other "constants" of the cable pair undergo variations with temperature, which in turn affect the attenuation. The magnitude of the result for a representative nonloaded 19-gauge cable pair is illustrated by the curves of figure 4, which show, respectively, the attenuation for an average temperature, assumed to be 55 degrees Fahrenheit, and for 0 and 110 degrees Fahrenheit. The latter values, often taken as the extremes of annual variation for an aerial cable, are in fact frequently exceeded. One reason for this is that when the sun is shining directly on an aerial cable, it may assume a temperature from 15 degrees to 25 degrees above that of the ambient air. The range of temperature variation (and attenuation variation) for an aerial cable may be half as much in one day as in an entire year. For an underground cable, changes of temperature occur quite gradually and the total annual variation is about one-third of that for an aerial cable.

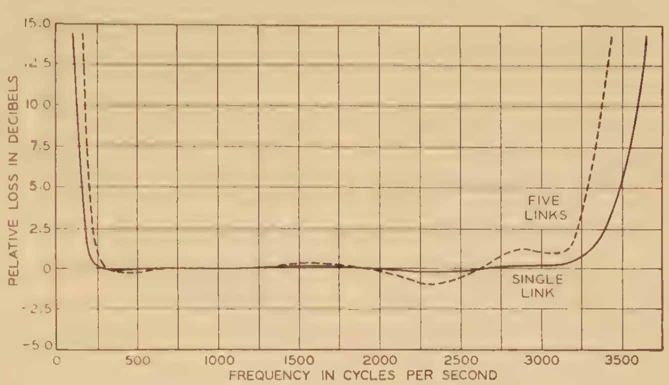

Figure 3. Transmission-frequency characteristics of over-all circuit

These relations between the attenuation of a cable pair and the frequency and temperature are of fundamental importance in the design of the type *K* system. First of all, since the attenuation at 60 kilocycles is about four decibels per mile, the total attenuation for a cable circuit of the length used in designing the type *K* system, i. e., 4,000 miles, would be approximately 16,000 decibels. This must be offset by a corresponding gain.

In the next place, differences in the attenuation at the different frequencies would, if uncorrected, become so great that signals of the less attenuated channels would overload the repeaters, while those of the more attenuated channels would drop down into the noise region. Hence, each repeater must be given a gain-frequency slope which is complementary to the attenuation slope of the line.

Finally, the changes of transmission due to temperature variations and other causes must be compensated so precisely that the net variation in each channel is held within very narrow limits. The method of doing this is explained later. Here it is interesting merely to consider the magni-

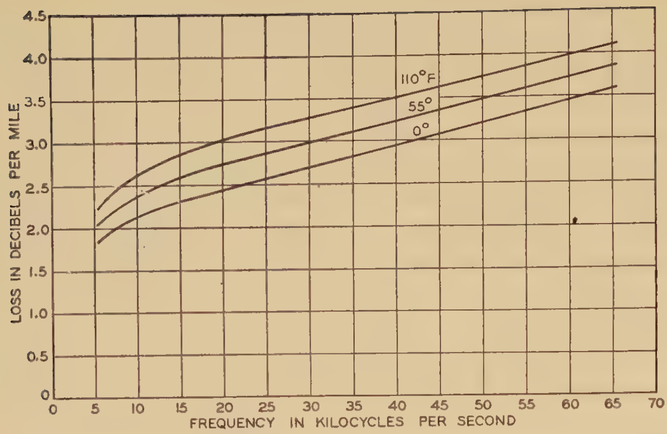

Figure 4. Attenuation of 19-gauge nonloaded cable pair

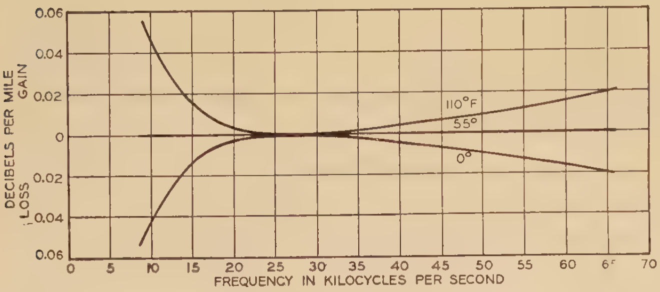

Figure 5. Twist characteristics of 19-gauge nonloaded cable pair

tude of the problem. For the top channel, assuming a 4,000-mile circuit, the annual variation in attenuation of an aerial cable pair might be approximately 2,000 decibels. The systems thus far installed have, of course, been limited to much shorter distances than this.

Even if the change of attenuation with temperature were related to frequency by a simple law, correct compensation over the frequency range would be far from easy. To a casual inspection the differential between any two curves of figure 4, for example those for 55 and 110 degrees Fahrenheit, will not appear serious. This differential, which becomes very large for a long circuit, is, however, a complicated function of the frequency.

The attenuation differential with temperature can be considered as made up of two components, one which is independent of frequency and another which varies with frequency. The former component, which is much the larger, requires a gain adjustment which is uniform or flat over the frequency range of the system. The latter component is frequently referred to as the "twist." For the range from 12 to 60 kilocycles, the maximum change of attenuation with temperature occurs near 28 kilocycles. Hence this frequency has been used as a datum point in determining the twist. The shape of the twist component is apparent from figure 5, which shows the net loss per mile at temperatures of 0 and 110 degrees Fahrenheit, assuming that the attenuation has been equalized so as to obtain a flat characteristic at 55 degrees Fahrenheit, and that the gain is then adjusted so as to hold the transmission constant at 28 kilocycles as the temperature varies.

Although the twist is small enough so that it need not be corrected at each repeater, it is too large to be allowed to accumulate over a very long distance.

CROSSTALK

As noted above, crosstalk between opposite directions of transmission is avoided by using two separate cables (or shielded compartments in the same cable). To prevent crosstalk in offices, special measures are employed. There remains the problem of "far-end" crosstalk between pairs in the same cable which transmit in the same direction. The pairs are packed closely together, and substantial crosstalk occurs between them because of small departures from symmetry and slight imperfections of twisting. However, by abandoning the use of phantoms and by connecting small adjustable mutual inductance coils between each carrier pair and every other carrier pair, sufficient crosstalk reduction is obtained to permit transmission up to 60 kilocycles on a substantial number of pairs.[4] The scheme is illustrated in figure 6.

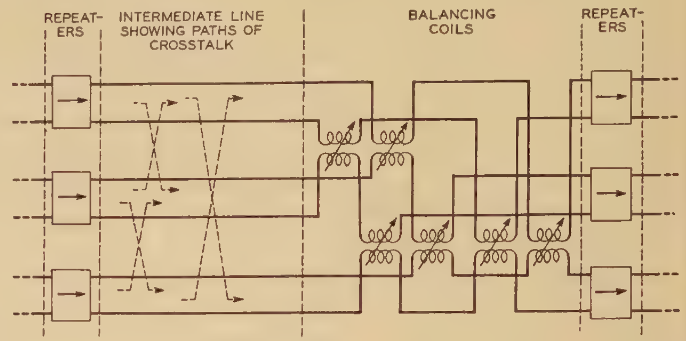

Figure 6. Method of balancing out crosstalk

In the original Morristown cable, the crosstalk was reduced in part by separating the 16-gauge carrier pairs from one another by 19-gauge quads which served as spacers. With existing cables, however, the use of spacers would be impracticable since this would require resplicing the cable at every joint, and therefore reliance must be placed largely on balancing. Since the number of combinations to be balanced increases approximately as the square of the number of pairs employed for carrier, the number of balancing coils required for even a moderate complement of carrier pairs becomes quite large. With 40 carrier pairs, for example, the number of coils required is 780. The balancing coils are mounted on panels as shown in figure 7 and are connected together in a crisscross arrangement. Each repeater section is balanced separately, the balancing panels being located in the repeater station.

Other measures are necessary to supplement this balancing technique. To reduce the crosstalk coupling, and also to average the transmission characteristics of different pairs, the carrier pairs in different quads of an existing cable are respliced about every mile so as to approach random splicing. The crosstalk coupling between the two sides of a quad is reduced by test splicing at the middle of a repeater section and the quads are split at repeater points.

In a new cable, of course, the desired splicing arrangements are introduced at the time of installation. The carrier pairs are also transposed from one cable to the other as indicated in figure 1. This avoids interaction crosstalk that would take place, through the medium of the voice-frequency pairs, between the high level carrier outputs on one side of a repeater station and the low level inputs on the other side. There is, of course, a similar effect between carrier pairs at any point in a repeater section. This is much less serious since no level difference is involved, but it does tend to limit the effectiveness of the balancing over a range of frequencies.

Reflections resulting from impedance irregularities reverse the direction of propagation and therefore produce far-end crosstalk from near-end crosstalk. This crosstalk cannot readily be balanced out over a range of frequencies. To avoid it, it is necessary that the impedances of successive lengths of cable pair be substantially uniform and also that the impedance of the equipment be closely matched to the characteristic impedance of the cable pair.

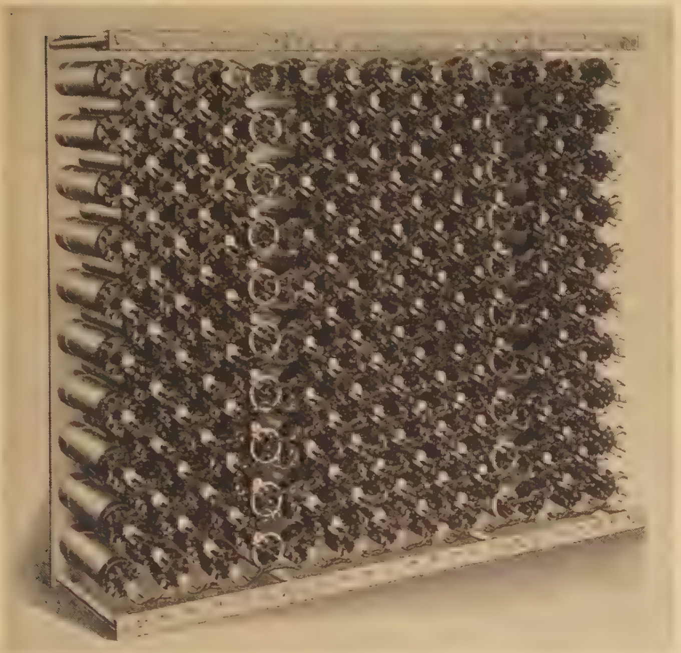

Figure 7. Crosstalk balancing panel

NOISE

The cable pairs are fairly well protected by the lead sheath from external electrical disturbances. However, high-frequency noise originating in the voice-frequency repeater stations due to relay operation, etc., would, unless prevented, enter the cable over the voice-frequency pairs and thence would be induced in the carrier pairs. Such noise would be excessive at the low-level carrier inputs. It is avoided by connecting, in each voice-frequency pair in the "low-level" cable on each side of a voice-frequency repeater station, a coil which supresses longitudinal noise currents. Similarly, it is necessary to keep high-frequency noise from entering the cable where open-wire pairs tap into it and frequently also where branch cables are connected. For this purpose simple noise-suppression filters are employed. With these and other measures the noise on the carrier pairs can, at the highest frequencies where the amplification is greatest, be brought within a few decibels of the basic noise due to thermal agitation of electricity in the conductors themselves.

VELOCITY OF TRANSMISSION

Voice waves travel through loaded cable circuits at from 10,000 to 20,000 miles per second, the higher speed being used for the longer circuits. On very long connections, even if echo suppressors are employed this velocity results in transmission delays which introduce difficulties in conversation.[5] The use of nonloaded conductors for the type *K* systems results in an over-all velocity of transmission of about 100,000 miles per second, a speed so high that such difficulties are greatly reduced and satisfactory telephone conversations are possible over the longest distances for which connections may be required.

Repeaters

Since the noise level in the cable circuits can be made quite low, the carrier currents may be permitted to drop to levels below those used on voice-frequency circuits or on open-wire carrier circuits, and the repeaters may have higher gains. In the cable carrier system the noise has been so reduced that the level of the top channel at the repeater input may on the average be dropped about 60 decibels below the voice level at the transmitting switchboard. The amplifier gains at the top frequency range from about 50 to 75 decibels and the output level of each of

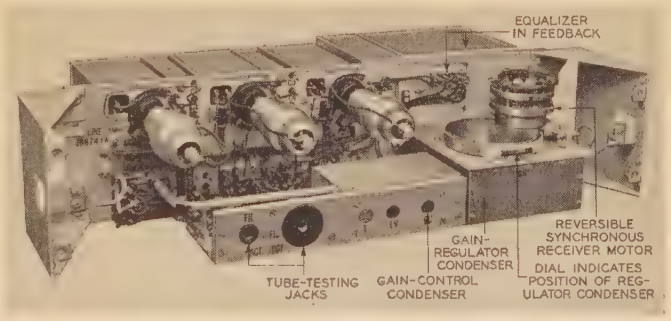

Figure 8. Line amplifier

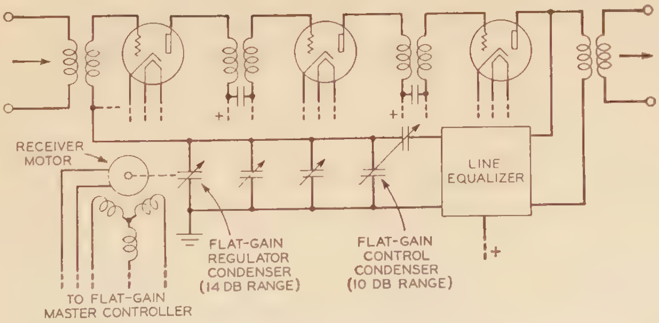
RECEIVER MOTOR
LINE EQUALIZER
+
+
+
FLAT-GAIN REGULATOR CONDENSER (14 DB RANGE)
FLAT-GAIN CONTROL CONDENSER (10 DB RANGE)
TO FLAT-GAIN MASTER CONTROLLER

Figure 9. Schematic of line amplifier

the 12 channels is about ten decibels above that at the switchboard. The average repeater spacing is about 17 miles.

The tube which was developed for the gain stage of the amplifier is a pentode with indirect heater. The heater requires a potential of ten volts and a current of 0.32 ampere and the plate, 150 volts. The tube in the power stage is similar in type but requires a heater current of 0.64 ampere at ten volts. With this power tube a feedback of about 40 decibels has been found to provide a satisfactory reduction of inter-channel modulation.[6] Both tubes were designed to have long life with very reliable performance.

DESCRIPTION OF AMPLIFIER

Each repeater comprises two amplifiers of the type illustrated in figure 8. A schematic diagram of the amplifier circuit is shown in figure 9. Three stages with impedance coupling are used and the feedback circuit is connected between the plate circuit of the last tube and the grid circuit of the first. The amount of gain and the slope of the gain-frequency characteristic are controlled by the condensers and line equalizer in the circuit.

The line equalizer has the same attenuation slope as the line. In the introduction of this equalizer in the feedback circuit careful attention to phase-shift requirements was required. Four types of equalizers are available, for different repeater spacings, to compensate for the cable distortion which occurs at a temperature of 55 degrees Fahrenheit, additional means being provided to compensate for variations which occur as the cable temperature swings away from this value. The solid curve of figure 10 shows a repeater gain characteristic with one of these equalizers in the feedback circuit.

The correction introduced by the line equalizers is subject to errors which, although small at each repeater point, become important for a moderate length of system. Supplementary equalizers have been designed to correct for these. Two types of deviation are considered, that of the cable and that of the amplifier. As the characteristics of cables manufactured at different times show slight departures from one another, two shapes are required to correct their deviations. There is one corrector for concave deviations and another for convex. The amplifier requires but one type of correction. The characteristics of these equalizers are shown in figures 11 and 12. The equalizers for amplifier deviations are used about every tenth repeater and those for the cable deviations at distances of 300 to 400 miles. At normal temperature (55 degrees Fahrenheit), the correction applied by these networks will, for a 500-mile system, result in a frequency characteristic which is flat to within less than two decibels over the range from 12 to 60 kilocycles. For a longer circuit further corrective measures will be provided.

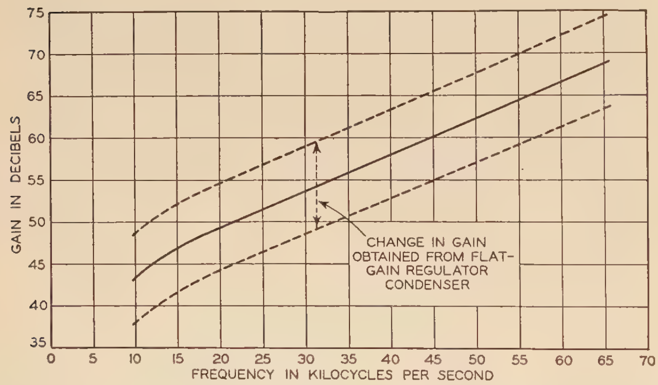

Figure 10. Amplifier gain characteristics

REGULATION FOR TEMPERATURE EFFECTS

The method adopted for controlling the repeater gain to compensate for temperature changes is similar to that which has been found satisfactory for voice-frequency cable circuits. This is the pilot-wire method in which a pair of cable conductors extending over the section to be regulated forms one arm of a Wheatstone bridge. This bridge is designed for automatic self-balancing and the mechanical motion required for establishing the balance has been made to adjust the gain of the amplifiers. The d-c resistance of the pilot wire gives an accurate indication of the temperature of the carrier pairs, which determines their attenuation to a close approximation. The motion of the bridge mechanism is communicated to the repeater amplifiers by means of self-synchronizing motors, a master motor being associated with the bridge and an individual motor with each amplifier.

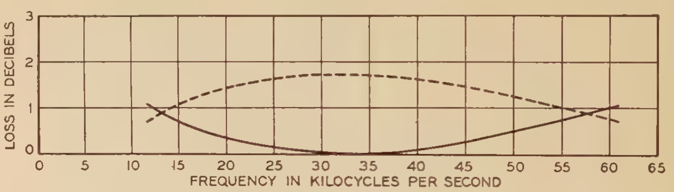

Figure 11. Characteristics of cable deviation equalizers

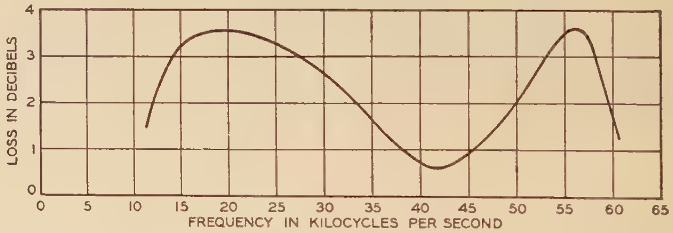

Figure 12. Characteristics of amplifier deviation equalizer

With aerial cable a flat gain correction must be made at every repeater. With underground cable the flat gain correction may be omitted at some repeater points. Figure 13 shows a master controller with its galvanometer, driving motor, and self-synchronizing motor. The air condenser in the feedback circuit of figure 8 makes this correction. The small self-synchronizing motor which may be seen in this figure is geared to the condenser and it moves the air condenser in accordance with the motion of the master motor. The resulting change in repeater gain is virtually the same for all frequencies in the transmitted band. In figure 10 the repeater gain is plotted against frequency for three angular positions of the condenser.

As was mentioned earlier, an additional correction for the residual effect or "twist" is required about every six repeaters to supplement the flat gain adjustment. This distortion is a function of frequency and has been found to vary from cable to cable. A network whose characteristics are shown in figure 14 has been developed to meet this condition. Certain fixed resistances in the network are selected to correspond to the length and twist characteristic of the cable section considered. A variable resistance in the network is adjusted automatically using a control similar to the flat gain regulator. Figure 15 gives the transmission characteristics of a 150-mile regulator-controlled circuit under two temperature conditions.

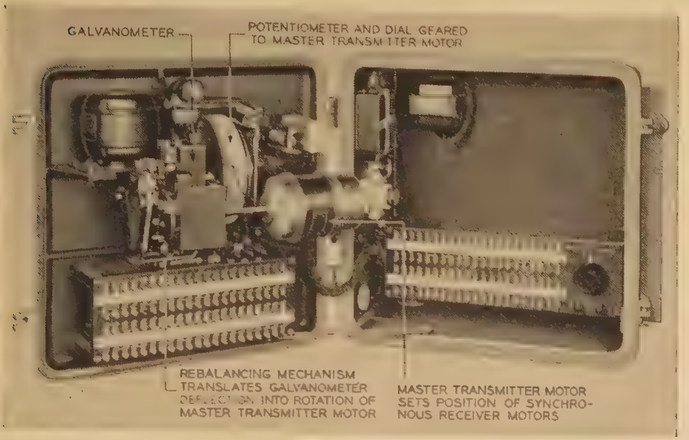
GALVANOMETER
POTENTIOMETER AND DIAL GEARED TO MASTER TRANSMITTER MOTOR
REBALANCING MECHANISM TRANSLATES GALVANOMETER DEFLECTION INTO ROTATION OF MASTER TRANSMITTER MOTOR
MASTER TRANSMITTER MOTOR SETS POSITION OF SYNCHRONOUS RECEIVER MOTORS

Figure 13. Flat gain master controller

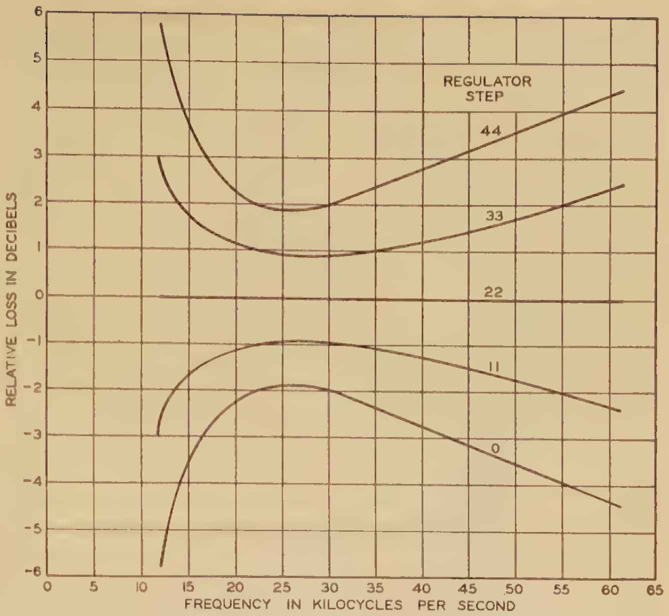

Figure 14. Characteristics of twist regulator networks

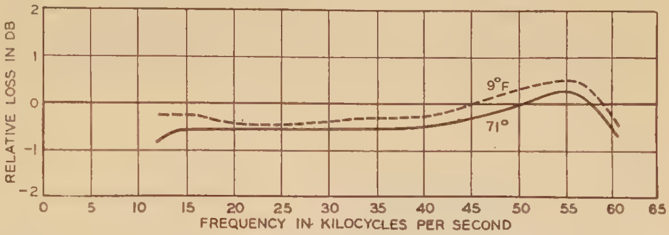

Figure 15. Over-all transmission-frequency characteristic of 150-mile line

Auxiliary Repeater Stations

Cable carrier systems are expected to be used largely on existing toll-cable routes which now carry voice-frequency circuits. The average spacing of the stations housing the voice-frequency repeaters on these routes is about 50 miles. The same buildings with their power plants will also care for the cable carrier repeaters. Since the maximum spacing for the carrier repeaters is about 19 miles, additional carrier repeaters must be provided at intermediate stations (two is the usual number). The various design features of the equipment to be located in these stations have been made the subject of extensive development work and field tests. These stations are designed to function with a minimum of attention and are visited at intervals for routine testing work or as required by some emergency, but resident maintenance forces are not planned for them. The present equipment is expected to be suitable not only for auxiliary stations on existing cable routes but also for cases where a greater spacing than 50 miles between the attended stations may be desired on new routes.

A voice-frequency repeater station for a single cable and a cable carrier auxiliary station are shown to approximately the same scale in figures 16*a* and 16*b*, respectively. Many of the existing voice-frequency stations are even larger than that shown in figure 16*a*. The auxiliary building shown in figure 16*b* has about 600 feet of floor space with a ceiling height sufficient to take care of 11-foot six-inch relay racks. This building will house 100 repeaters with necessary auxiliary equipment, thus providing ultimately for a total of 1,200 carrier circuits. The interior of a typical auxiliary station is shown in figure 17.

The main power plant for the repeaters consists of a 152-volt storage battery, which is continuously floated across a grid-controlled rectifier fed from the 60-cycle power mains. The voltage of the entire battery applies the plate voltage for the tubes. Each amplifier requires about 22 volts for the tube heaters and this is obtained by dividing the battery into seven sections, each section supplying several amplifiers in parallel. Additional power supplies of 55 volts alternating current and 140 volts direct current are required for the regulator system.

In the station, there are alarm circuits, which signal the nearest attended office if trouble develops. There are alarms for blown fuses, high or low battery voltages, power failures, etc. A telephone order wire to the nearest attended station is provided for the maintenance force.

In addition to the line amplifiers with their regulating equipment, there are racks mounting the crosstalk-balancing coils. There are also sealed terminal units between the outside cable or the balancing units and the office cable. These furnish access to the line or equipment through jacks.

Terminals

The minimum distance over which a cable carrier system can be operated economically is determined in large measure by the cost of the terminal apparatus. Hence, the field of usefulness of the system is greatly increased by keeping the terminal cost as low as is consistent with satisfactory performance. Numerous developments during the past few years in connection with modulation, filtering, and methods of carrier supply have all contributed materially toward this end. At the same time, the standards of performance have not only been maintained, but in many respects substantially improved.

Figure 16a (above). Voice-frequency repeater station on single cable route

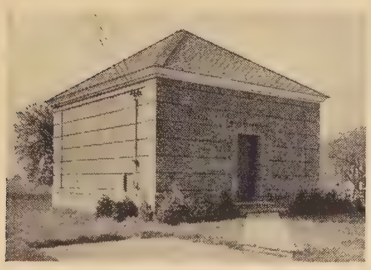

Figure 16b. Auxiliary cable carrier repeater station

CHANNEL AND GROUP MODULATION

In the design of the terminals for the type *K* system, a number of circuit arrangements were considered, the final choice being influenced to a considerable extent by the conditions imposed upon the filters. As noted above, the desirability of using the channel terminal equipment in other broad-band systems such as those for open wire or coaxial cable was also an important factor. The circuit arrangements selected have a first stage of modulation which raises the voice frequencies of the 12 channels up to a range of 60 to 108 kilocycles. This range is favorable to the use of crystal type band filters,[7] which have transmission characteristics superior to the coil and condenser type and seem to be no more costly. For the type *K* system, a single stage of group modulation shifts the frequencies to the range required on the line, 12 to 60 kilocycles and a similar stage at the receiving end returns them to the 60 to 108-kilocycle range. Other carrier systems will also use the 60 to 108-kilocycle channels and by group modulation shift them to the desired position in the frequency spectrum.

The band filter occupies a space on the relay rack equal to one-eighth of that required by the coil and condenser type which was used in the earlier model of this system. Its attenuation characteristic in the transmitting region is flat to within one decibel over a range of about 3,100 cycles. Immediately outside of this range the attenuation rises very rapidly, thus permitting very efficient use of the frequency spectrum.

Another new device on the terminal is the copper-oxide unit used in the modulating process. These units are expected to show a stability of the same order as that of coils and condensers, and require practically no maintenance as compared to vacuum tubes.

The translation of the channels from the 60 to 108-kilocycle range to the position required for cable carrier, 12 to 60 kilocycles, is made by a stage of group modulation. A copper-oxide group modulator is used and a carrier frequency of 120 kilocycles. The reverse of this process in a similar group demodulator at the receiving end steps the frequency back to its original range, 60 to 108 kilocycles. These processes of modulation take place at points of low energy level in the circuit with a comparatively high level of carrier, so that the interchannel crosstalk which results from unwanted products of modulation is unobjectionable. Low-pass filters are inserted after the group modulator and demodulator, and amplifiers with

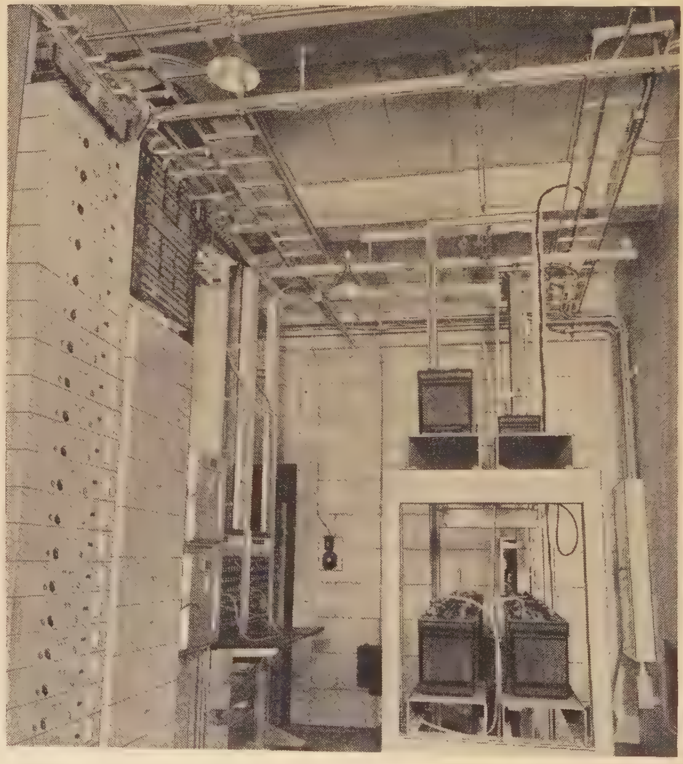

Figure 17. Interior of auxiliary repeater station

flat gain characteristics are supplied to raise the levels of the output currents of the group modulators or demodulators.

Carrier Supply

The carrier frequencies which are required at a terminal are obtained from the harmonics of a base frequency. The carrier supply system is common to as many as ten systems in one office. This simplification was made possible by the selection of the channel frequencies as multiples of a base frequency, four kilocycles being chosen for this system. This base frequency is produced by an oscillator in which the control element is a tuning fork, the whole unit being designed to have the necessary output and frequency stabilities. The output of the oscillator is amplified and fed to a circuit which produces the desired harmonics. All of the carrier frequencies which are required for the different channels as well as for group modulation and demodulation are obtained from these harmonics. A small coil with a permalloy core is the important agent in this process.[8]

Failure of the four-kilocycle supply, or failure of the 120-kilocycle supply used for group modulation, would cause failure in the channels of all systems operating from this supply. Provision is made for such a contingency by an emergency carrier supply which is automatically switched into service when the regular supply fails. This reserve source duplicates all of the parts of the regular supply, four-kilocycle fork, amplifier, harmonic producer, and amplifier for the 120-kilocycle carrier.

Assembly

The different panel units which make up the terminal of a type *K* system are assembled on a functional basis with similar panels of other *K* systems, the channel modulator-demodulator panels in one bay, the carrier supply in a second, the group modulator and demodulator in a third, etc. The compactness of the equipment makes it possible to mount the modulators and demodulators for 18 channels on one 11-foot six-inch bay 19 inches wide.

Signaling

The same type of ringdown signaling equipment is used with the channels of this system as with the voice-frequency toll circuits. A 1,000-cycle tone, interrupted 20 times per second, is impressed on a channel terminal, modulated, and transmitted over the carrier system in the allotted channel band. At the far end, it is demodulated to operate the receiving end of the standard voice-frequency receiving circuit, or to be transmitted along an extended voice-frequency circuit to its terminal.

Telegraph and Program Applications

Voice-frequency telegraph can be superposed on any of the carrier channels as is now done on the three-channel open-wire systems. Equipment is being developed to superpose a program channel on the cable carrier system. This will be done by devoting to the program circuit the frequency space occupied by two of the four-kilocycle speech bands.

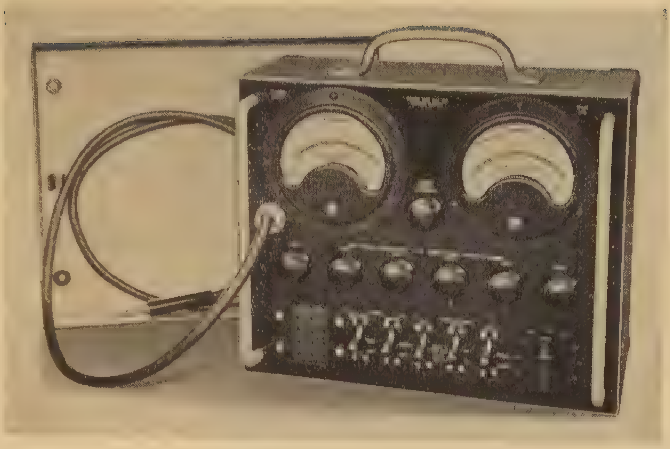

Figure 18. Vacuum tube test set

System Maintenance

Arrangements are provided whereby the tubes may be tested on a routine basis as has been done in voice-frequency practice. The amplifier panels, however, are provided with test jacks which are connected to resistances in the plate circuits. A reading of the voltage across the resistance gives a measure of the plate current for the associated tube without disturbing the amplifier performance while the amplifier is in service. A portable tube testing set, figure 18, has been designed for this measurement.

Provision is being made for the removal of an amplifier from an active circuit without interruption of service. A spare amplifier at each repeater station can be substituted for the active one by connecting it to jacks at the sealed terminal and operating associated relays to make a quick transfer.

Apparatus is also furnished which permits the substitution of a new link between attended points for one which develops trouble. A complete high-frequency circuit for each direction of transmission will generally be reserved as a spare. It can be substituted for any working high-frequency circuit without interfering with service by paralleling the transmitting ends of the spare and working circuits and patching the receiving ends through relays. The operation of a key controlling these relays substitutes the spare circuit for the working one with a transient disturbance of but one or two milliseconds.

Three pilot frequencies, 15.9, 27.9, and 55.9 kilocycles, which are produced at the transmitting terminals, may be used to check the levels at the main repeater points and the receiving terminals. This is done by means of a special testing circuit which can be bridged across a pair to detect the level of the pilots without interference to service.

A heterodyne oscillator having a frequency range from 60 cycles to 150 kilocycles has been developed for use in testing this and other carrier systems. Its frequency is calibrated at 60 cycles against the power mains and at 100 kilocycles against a quartz crystal. This oscillator is shown in figure 19. A portable test set, developed for measuring transmission gains and losses with high precision, is shown with the cover removed in figure 20.

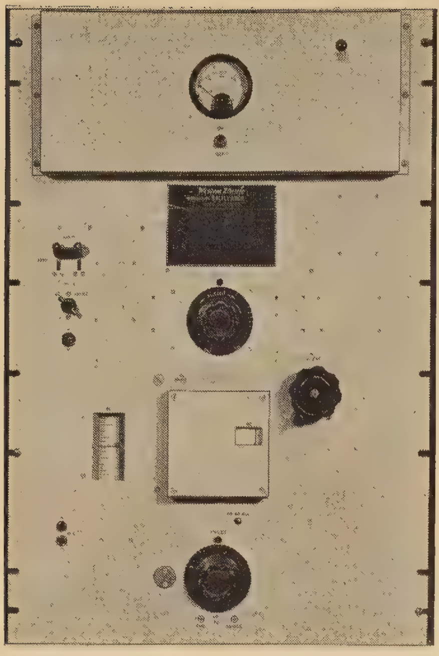

Figure 19. Testing oscillator

Conclusion

The type K system makes possible the application of carrier to toll cables of existing type, whether installed underground or aerially. The blocks of 12 circuits each, which it furnishes, seem to be a convenient size for routes where large numbers of circuits are concentrated. It is to be expected, of course, that substantial modifications and improvements will be made in this system through further development effort. In its present form, however, it constitutes an important stage in the history of carrier development. Plans already under way call for the application of large numbers of such systems to meet rapid growth in long-distance traffic.

This new system forms merely one phase of a concerted development effort on broad-band carrier transmission systems.[9,10] There is every indication that, taken collectively, these broad-band systems will have far reaching effects upon the toll telephone plant of the Bell System. A transition is already under way from the time when carrier was used only on open wire, and comprised only a small part of the toll plant, to a time when carrier systems will furnish a major part of the toll circuit mileage of the Bell System. The type K system is clearly destined to play an outstanding part in this evolution of the toll plant along carrier lines.

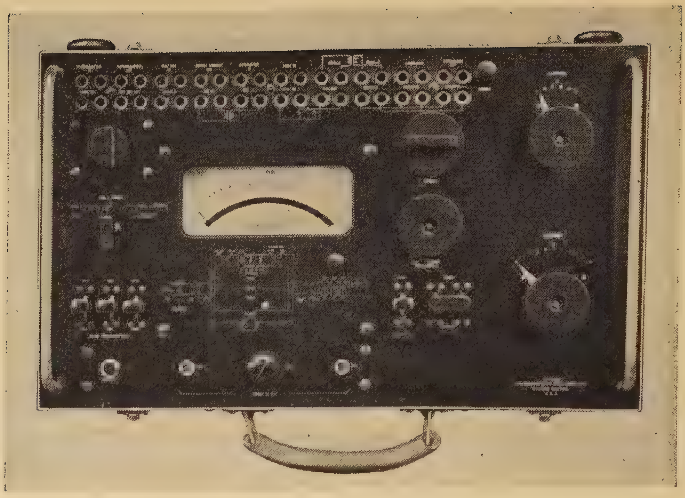

Figure 20. Transmission measuring set

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Discussion

For discussion of this paper see page 259.

Cable Carrier-Telephone Terminals

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Synopsis: This paper describes the circuits, performance, and equipment features of the terminals of a new 12-channel carrier system for application to existing toll cables. The 12-channel group of terminal apparatus has been designed also to form a basic part of the terminals of other carrier systems now under development, such as the type-*J* system for open wire and the coaxial system.

Introduction

ABOUT 20 years ago the first commercial carrier telephone system was installed between Baltimore and Pittsburgh. Until recently, telephone circuits were obtained by carrier methods largely on open-wire lines. The notable exceptions were on short deep sea submarine cables.[1,2] Ten years ago, experiments were initiated which now have resulted in the design of a carrier system which can be applied with substantial economy to existing long distance toll cables on land. Its general features are described in another paper.[3] The present paper describes in detail the circuits and performance of the carrier terminals of this system.

General Features

The carrier system for existing cables, designated type *K*, is designed to provide 12 telephone channels in the frequency range between 12 and 60 kilocycles, using one nonloaded 19-gauge paper insulated cable pair in each direction. Previous carrier systems employed for open-wire lines used vacuum tubes for the modulating or translating circuits and electrical filters composed of coil and condenser networks for separating the frequency bands associated with the respective channels. The terminals of the new type-*K* system are simpler and yet provide improved performance by using copper-oxide bridges for the modulation function and quartz-crystal filters[4] for the separation of the individual channel bands.

The quartz-crystal filter is economical only in a comparatively high frequency range, necessitating the use of high intermediate frequencies. The high intermediate frequencies are reduced by a second stage of modulation to the desired range of frequencies for transmission over the line. Copper-oxide bridge circuits again are used for this group-modulation stage. In all cases they are connected to suppress the carrier. To provide the various carriers required for modulation and demodulation, a carrier supply system has been designed somewhat along the lines of an office power-distribution system using bus bars and protective arrangements for the various carriers. Each carrier supply system is capable of supplying as many as ten carrier terminals, or a total of 120 two-way channels.

Because of the large number of circuits involved, every effort has been made to provide reliable operation of the carrier supply and common terminal equipment. The terminal and carrier supply equipment is designed to permit maintenance tests for checking the performance of amplifier tubes and to permit switching between regular and spare equipment without interruption of the large number of circuits involved.

The emphasis placed upon ease of maintenance and the necessity for more careful handling of higher frequency circuits have resulted in new equipment design features. These include new cable terminals, new shielded office cabling, and panels arranged for front wiring and maintenance which are mounted on racks having wiring ducts at both edges of the bays. In the following sections a more detailed description is given of the circuits, their performance, equipment, and maintenance features.

Circuits

The frequency allocation for one direction of transmission and a block schematic of one terminal are shown in figures 1 and 2 which supplement each other and need little explanation. The 12 voice bands shown at the left in figure 1 are modulated individually in the channel modems. (The term "modem" has been coined to mean a panel or equipment unit in which there is both a modulator and a demodulator to take care of both the outgoing and incoming signal.) This forms a 12-channel block lying between 60 and 108 kilocycles which is then modulated in the group modulator by a 120-kilocycle carrier to move the block down in the range from 12 to 60 kilocycles for transmission to the distant terminal. On the receiving side the processes are reversed. One of the channels as well as the group modem of figure 2 is presented in more circuit detail in figure 3. This shows the circuit from the point where the voice comes into the carrier system to the point where the 12 carrier sidebands go out onto the cable and vice versa.

At the left the four-wire terminating circuit serves, not only as a device to transform from a two-wire to a four-wire circuit, but also as a high-pass filter to eliminate, from the input to the carrier system, noises below about 200 cycles, such as telegraph harmonics, 20-cycle ringing, 60-cycle power, etc., which may be present on connected voice-frequency circuits. Otherwise these noise frequencies which are below the voice range would modulate and pass through the terminal to load unnecessarily the carrier repeaters along the line, as well as to interfere with the level indications of the pilot channels.

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R. W. Chesnut, L. M. Ilgenfritz, and A. Kenner are all members of the technical staff of the Bell Telephone Laboratories, Inc., New York, N. Y.

[1] For all numbered references, see list at end of paper.

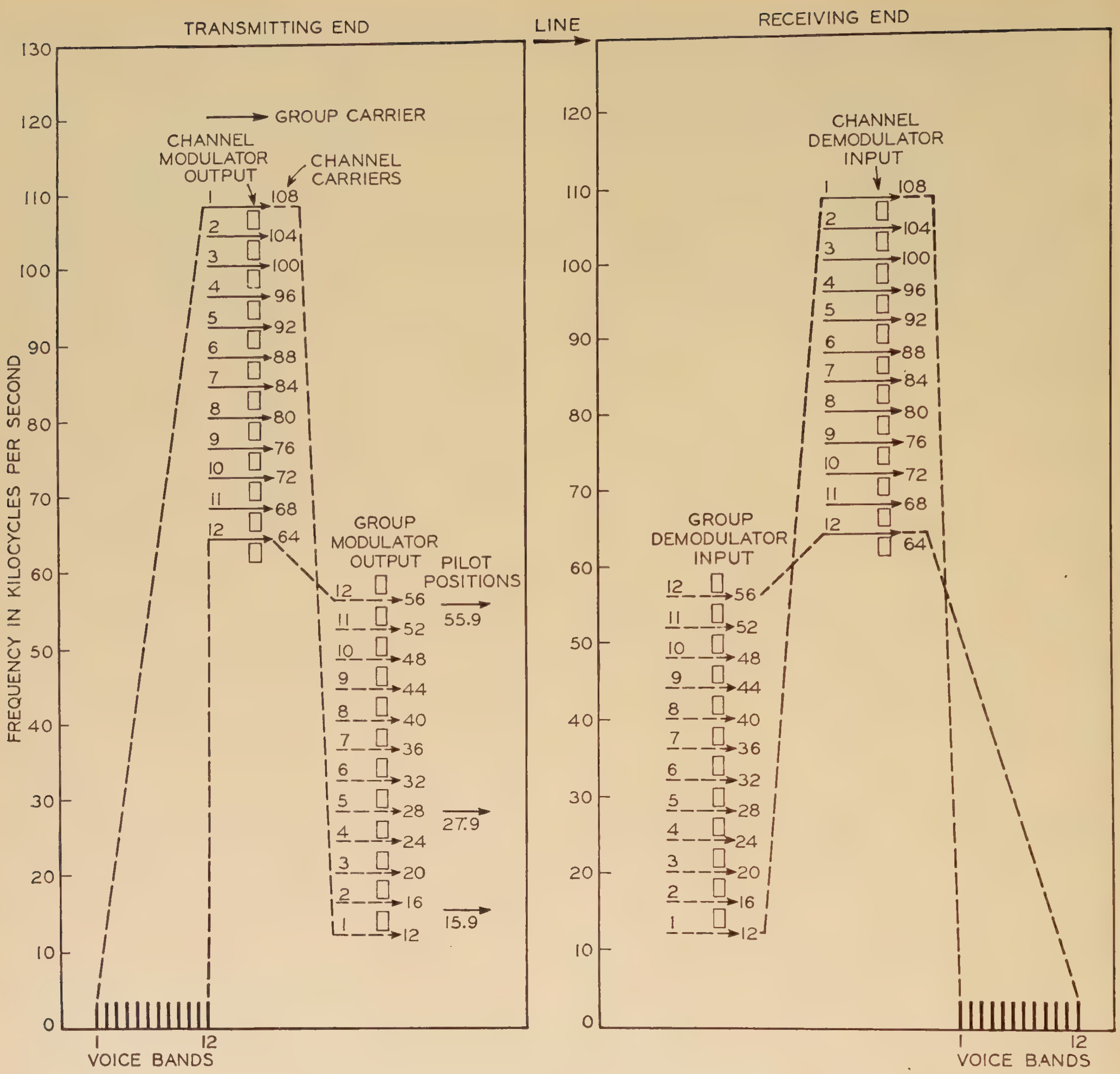

Figure 1. Frequency allocation

From the terminating equipment the circuit loops through jacks which have paralleled contacts for reliability. The level at this point is −13 decibels compared with the transmitting toll switchboard, which level is expected to be generally used in the Bell System for all multichannel carrier-telephone systems. Then comes the channel modulator which consists of four copper-oxide disks, each three-sixteenths of an inch in diameter, potted in a small can. This makes a very simple and inexpensive modulator which is much more satisfactory than tubes. It seems to have an indefinite life (some have been on life tests as modulators for about five years). The carrier power required is about one-half milliwatt to modulate satisfactorily a single telephone circuit level of −13 decibels.

The modulator produces the usual two sidebands and the lower one is selected by the quartz crystal channel filter described in another paper.[4] This sideband, joined by eleven others, is stepped down to about the iterative impedance of the shielded office cabling. In the office cabling the 12 channels pass through the high frequency patching bay to the double balanced group modulator of copper oxide where they are joined by three pilot-channel frequencies.

The group modulator uses the same copper oxide as that in the channel modulator described above, but the carrier power is about 50 times greater (about 25 milliwatts) in order to keep down unwanted modulation produced between the 12 sidebands. To that same end the level of each sideband is made low (−46 decibels), and the double balanced type of circuit is used to balance out some of the undesired products. It also balances out the

12 incoming bands in the range 60 to 108 kilocycles from the output and so simplifies the following group modulator filter.

From a level of −57 decibels the 12 channels, now in the range from 12 to 60 kilocycles, are amplified to +9 decibels for delivery to the 19-gauge pair in the lead covered toll cable. The amplifier is a three-tube negative-feedback type, using pentodes and operating with 154 volts plate battery which is composed of the usual 24-volt filament battery and 130-volt plate battery in series. The last tube is a power tube and does not overload until a single-frequency output of about one watt is reached.

On the receiving side in figure 3, the 12 incoming channels, in the range from 12 to 60 kilocycles, pass from the amplifying and regulating equipment,[3] to the group demodulator. This is identical with the group modulator described above and transfers the 12 channels to the range 60 to 108 kilocycles. The channels are then amplified to a −5 decibel level by an amplifier of the negative-feedback type using two low-power pentodes with 154-volt plate battery as described above for the transmitting amplifier.

From there the 12 channels are separated by the filters which are identical with those on the transmitting side, and are then demodulated and amplified to a +4 decibel level as shown for one channel in figure 3. The demodulator is identical with the modulator but it is poled oppositely on the carrier supply so that the d-c components of modulation in the modulator and demodulator neutralize each other and thereby avoid developing an undesirable voltage bias. The poling also reduces somewhat the amount by which stray frequencies have to be suppressed in the carrier supply. The demodulator amplifier has a slide-wire gain-control rheostat to equalize channel levels which functions by changing both the grid bias on the tube and the amount of negative feedback which is introduced by the rheostat. The sliding contact in the slide wire is made practically free from contact trouble by the space current of the tube flowing through it. As the rheostats are only about 1,000 ohms and small in size, they can easily be mounted at a distance from the amplifier in the voice-frequency jack field.

The carrier supply for the 12 channels from 64 to 108 kilocycles, and for the group modems of 120 kilocycles, is derived in the circuit shown in figure 4. A regular generator is shown at the top in solid lines and an emergency generator at the bottom is shown in dotted lines. Between the two is an automatic transfer circuit (in dotted lines) which transfers to the emergency whenever the regular generator fails to supply the proper amount of 120 kilocycles to the 120-kilocycle bus.

At the upper left-hand corner is shown a four-kilocycle tuning fork, of an alloy having a low temperature coefficient driven by the tube to its right to operate as an oscillator of very stable frequency. The next, or control tube, amplifies the four kilocycles to drive the push-pull power stage where a power of about four watts is developed. This passes through the four-kilocycle filter to the nonlinear coil where odd harmonics of four kilocycles are produced. The underlying principles of operation of this coil have been published.[5] To derive even harmonics of four kilocycles, the copper-oxide bridge is used which rectifies about half the energy of the complex wave of odd harmonics but, by balance, greatly reduces the amount of the odd harmonics present in its output. Odd harmonics are obtained at one point and even at the other. This separation into odd and even harmonics by the balance of the copper-oxide bridge provides effective loss of about 30 to 40 decibels and reduces the requirements on the carrier-supply filters which follow.

The two branches pass through hybrid coils to the banks of channel-carrier supply filters. These separate the frequencies and feed them to 12 carrier-supply bus bars, one for each channel frequency. From these the individual modems are fed through protective resistances so that an accidental short circuit on one of the modems will not cut off the carrier supply to the others.

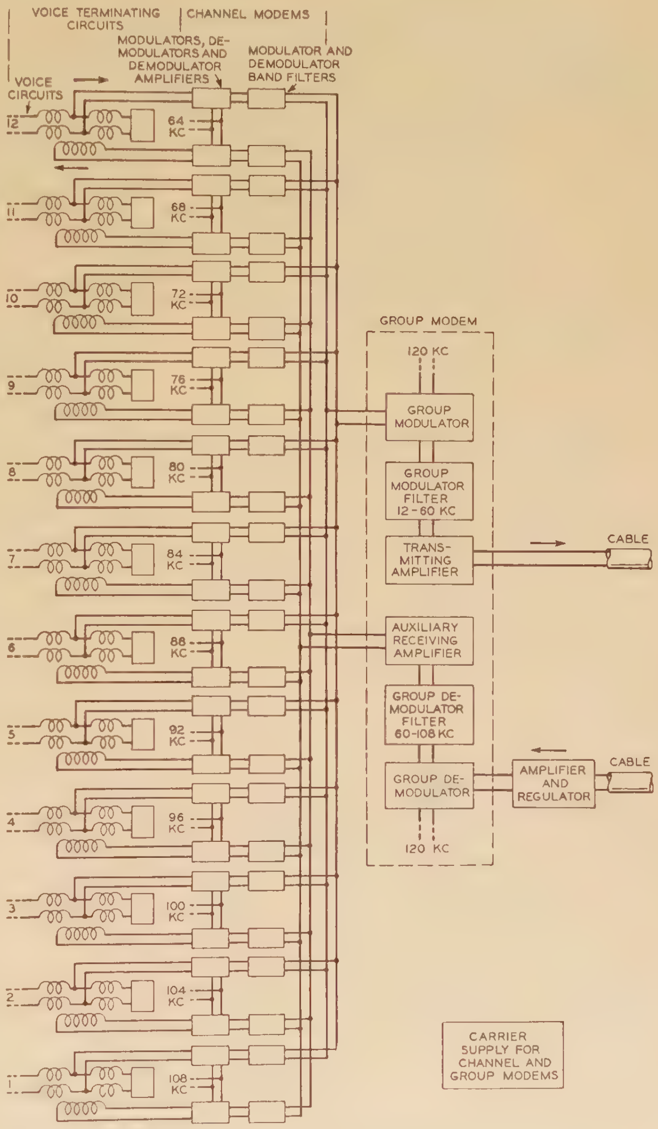
VOICE TERMINATING CIRCUITS
CHANNEL MODEMS
MODULATORS, DEMODULATORS AND DEMODULATOR AMPLIFIERS
MODULATOR AND DEMODULATOR BAND FILTERS
VOICE CIRCUITS
12
64 KC
11
68 KC
10
72 KC
9
76 KC
8
80 KC
7
84 KC
6
88 KC
5
92 KC
4
96 KC
3
100 KC
2
104 KC
1
108 KC
GROUP MODEM
120 KC
GROUP MODULATOR
GROUP MODULATOR FILTER 12-60 KC
TRANSMITTING AMPLIFIER
CABLE
AUXILIARY RECEIVING AMPLIFIER
GROUP DEMODULATOR FILTER 60-108 KC
GROUP DEMODULATOR
AMPLIFIER AND REGULATOR
CABLE
120 KC
CARRIER SUPPLY FOR CHANNEL AND GROUP MODEMS

Figure 2. **Block schematic**

The hybrid coils permit the two generators to be connected so that either can feed into the same bank of chan-

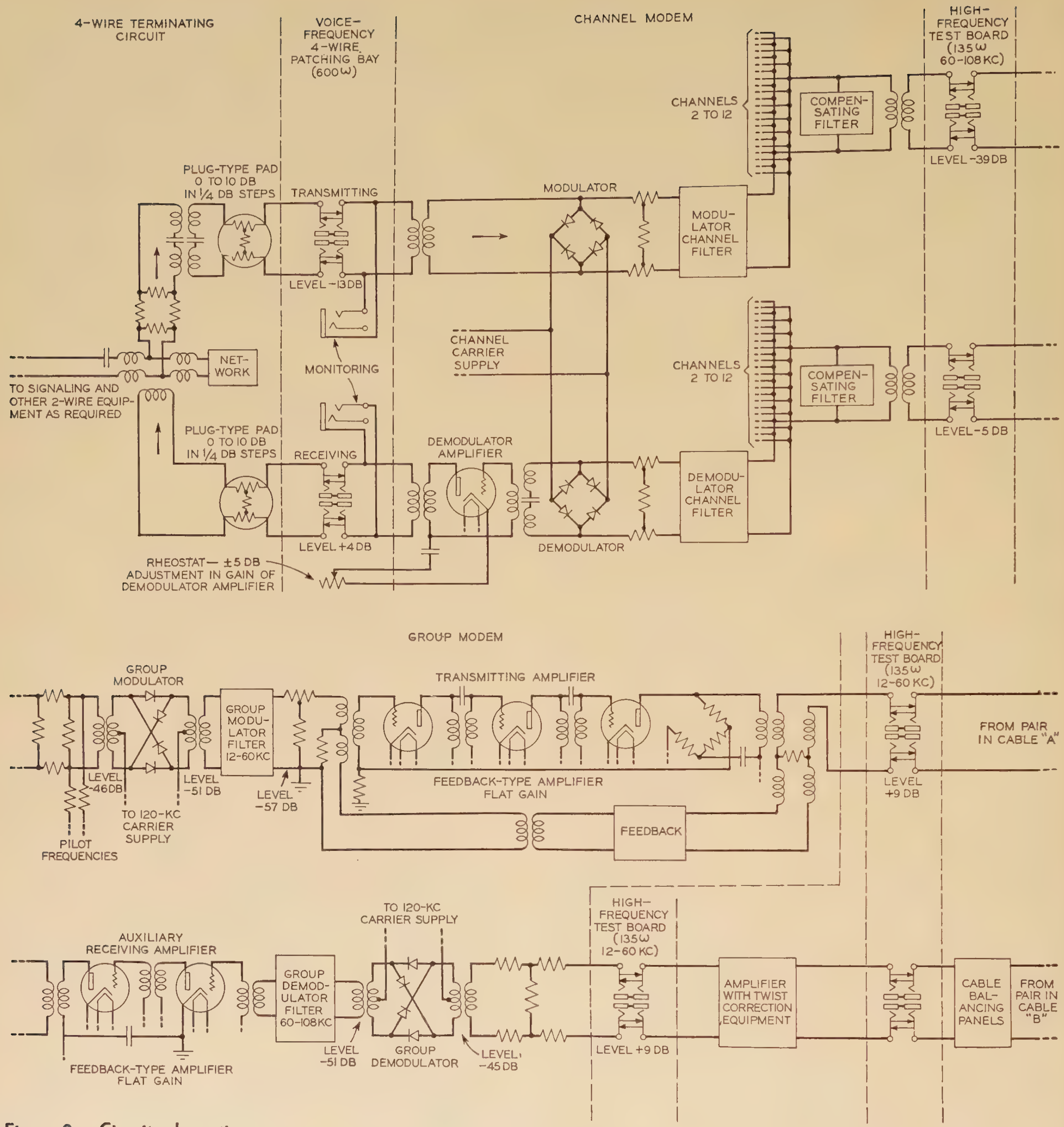
4-WIRE TERMINATING CIRCUIT
VOICE-FREQUENCY 4-WIRE PATCHING BAY (600ω)
CHANNEL MODEM
HIGH-FREQUENCY TEST BOARD (135ω 60-108KC)
CHANNELS 2 TO 12
COMPENSATING FILTER
LEVEL -39DB
PLUG-TYPE PAD 0 TO 10 DB IN 1/4 DB STEPS
TRANSMITTING
MODULATOR
MODULATOR CHANNEL FILTER
LEVEL -13DB
CHANNEL CARRIER SUPPLY
MONITORING
CHANNELS 2 TO 12
COMPENSATING FILTER
LEVEL -5 DB
NETWORK
TO SIGNALING AND OTHER 2-WIRE EQUIPMENT AS REQUIRED
PLUG-TYPE PAD 0 TO 10 DB IN 1/4 DB STEPS
RECEIVING
DEMODULATOR AMPLIFIER
DEMODULATOR CHANNEL FILTER
LEVEL +4 DB
DEMODULATOR
RHEOSTAT— ±5 DB ADJUSTMENT IN GAIN OF DEMODULATOR AMPLIFIER
GROUP MODEM
HIGH-FREQUENCY TEST BOARD (135ω 12-60 KC)
GROUP MODULATOR
TRANSMITTING AMPLIFIER
GROUP MODULATOR FILTER 12-60KC
FROM PAIR IN CABLE "A"
LEVEL -46DB
LEVEL -51 DB
LEVEL -57 DB
FEEDBACK-TYPE AMPLIFIER FLAT GAIN
LEVEL +9 DB
TO 120-KC CARRIER SUPPLY
PILOT FREQUENCIES
FEEDBACK
TO 120-KC CARRIER SUPPLY
HIGH-FREQUENCY TEST BOARD (135ω 12-60 KC)
AUXILIARY RECEIVING AMPLIFIER
GROUP DEMODULATOR FILTER 60-108KC
AMPLIFIER WITH TWIST CORRECTION EQUIPMENT
CABLE BALANCING PANELS
FROM PAIR IN CABLE "B"
LEVEL -51 DB
GROUP DEMODULATOR
LEVEL -45 DB
LEVEL +9 DB
FEEDBACK-TYPE AMPLIFIER FLAT GAIN

Figure 3. Circuit schematic

— NOTE —
LEVELS ARE SHOWN WITH RESPECT
TO THE TRANSMITTING TOLL SWITCHBOARD

nel carrier supply filters without being reacted upon by the other. No switching is required when changing from regular to emergency supply.

The 120-kilocycle carrier which feeds the group modulators of ten systems or a total of 120 talking channels must be very dependable. Therefore separate filters are used for the regular and emergency supply and separate amplifiers for the large power required by group modulators. Regular and emergency distributing busses are provided. Each group modulator and each group demodulator is wired through protective resistances to the regular bus and through another set of protective resistances to the emergency bus. With this arrangement an accidental short circuit even across one of the busses or across one of the output coils of one of the 120-kilocycle amplifiers will not stop the whole supply of 120 kilocycles.

The four-kilocycle oscillator of the emergency generator is in constant operation so that when it is needed no time is required to start it, but the grid bias on the second tube is held above its cutoff value by the automatic transfer circuit. This prevents the four kilocycles from going further until called for in an emergency.

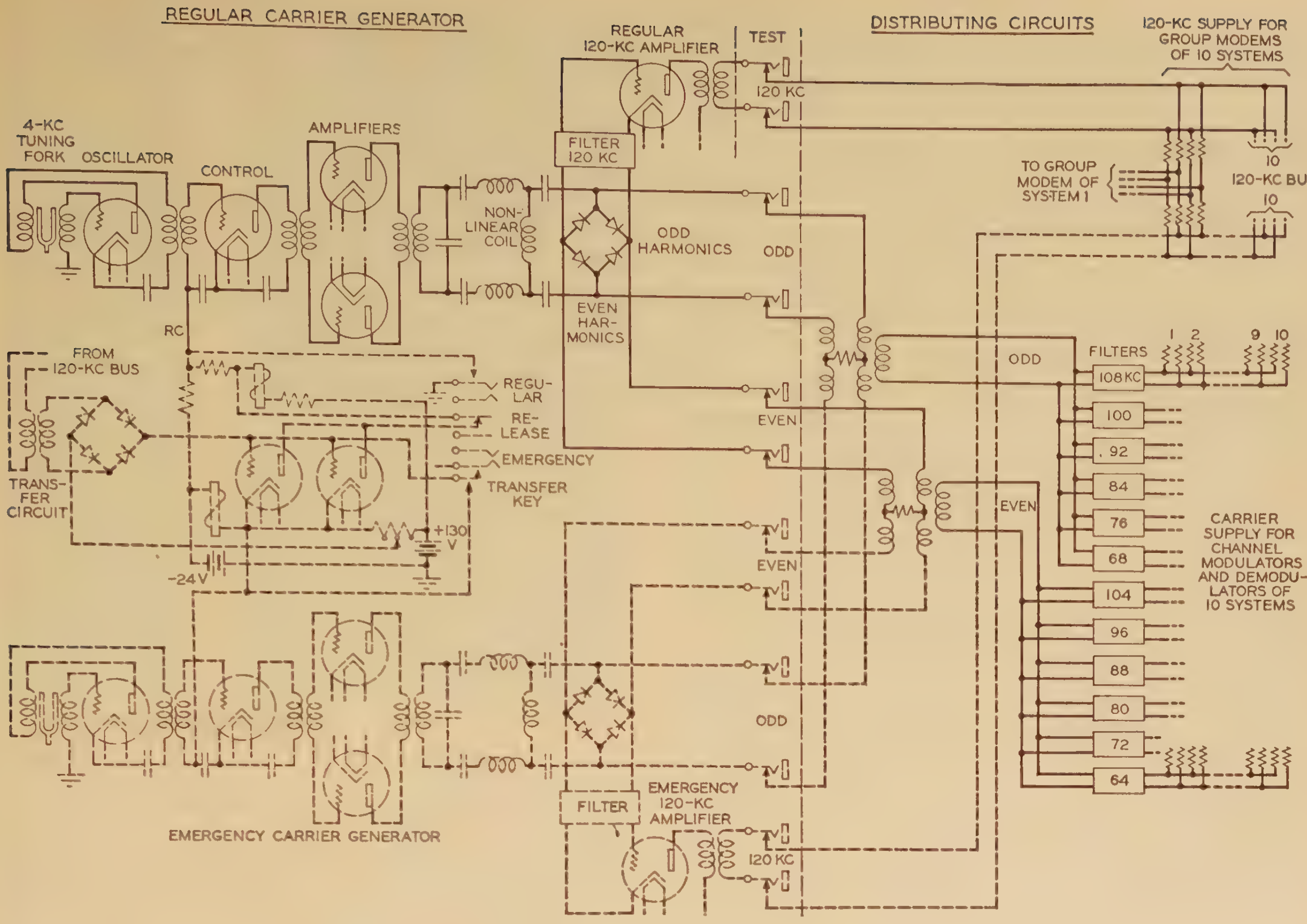

Figure 4. Carrier-supply circuit

An emergency is indicated when there is no 120-kilocycle supply on either the regular or emergency bus. When this happens, the copper-oxide rectifier in the transfer circuit gets no 120 kilocycles and so loses its rectified voltage. This triggers off one or both of the two gas-filled tubes (multipled for safety) which increases the grid bias on the control tube of the regular generator to stop its four-kilocycle supply and at the same instant restores the bias to normal on the control tube of the emergency to let its four kilocycles pass through and put the whole emergency circuit into operation. The keys in the transfer circuit are provided for maintenance purposes and to return from emergency to regular operation, since the gas tube circuit is arranged to transfer automatically in only one direction.

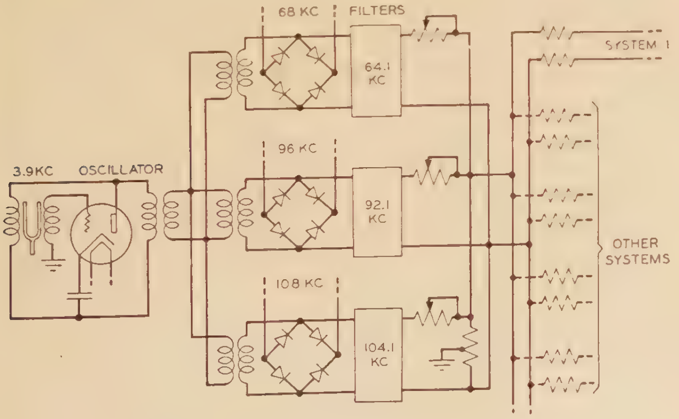

Figure 5. Pilot supply circuit

The pilot supply circuit is shown in figure 5. The 3.9-kilocycle tuning-fork oscillator at the left supplies that frequency, through the three transformers, to the three copper-oxide modulators whose carriers are obtained from the regular channel-carrier supply busses as shown. The three filters, which are identical with channel-carrier supply filters, select the lower sidebands to be used for pilot frequencies at 64.1, 92.1, and 104.1 kilocycles. The three pilot frequencies are distributed to the different systems through protective resistances from a bus as shown. They are set 100 cycles off the carrier frequencies to obtain locations of minimum interference from carrier leak and other sources.

Signaling circuits do not form an integral part of the carrier terminal equipment. Signaling equipment of a type already widely used in the Bell System for toll circuits, is connected between the toll switchboard and the four-wire terminating set of the individual channel.

Transmission Performance

In general, the performance requirements set down as objectives in the development of this system were based on the assumption that five carrier links operating in tandem and over a 4,000-mile circuit should give satisfactory, high-grade service.

The channel-frequency characteristic which has been attained in the terminals is shown in figure 6. The solid curve below shows the frequency characteristic of a representative channel, while the dotted curves near it show the limits within which the characteristics of all single channels, so far measured, would fall. Above in the figure is shown the characteristic of five representative channels in tandem, each channel having its two voice terminating circuits included.

The delay distortion and time of transmission, contributed by all terminal apparatus at both ends of a system, are shown in figure 7 for a single channel.

The channel modulators have been adjusted so that they will cut off the peaks of excessively loud talk to prevent overloading the carrier repeaters or other parts of the circuit, but this cutting is not enough to degrade the quality of speech. The single frequency load curve of one complete channel is plotted in two ways in figure 8.

The frequency stability of the oscillating tuning forks is expected to be within ± 1 × 10^{-6} per degree Fahrenheit on all systems, with negligible variations due to other causes. The amplitude stability of each frequency at its distributing bus is expected to be within ± $^1/_4$ decibel over a period of months. The impedances of the busses are sufficiently low so that crosstalk from one system into another through this path is unimportant. The effectiveness of the protective resistances at the carrier supply busses is such that a short circuit on one modulator or demodulator will increase the loss in the remaining modulators and demodulators less than one-half decibel. The speed of switchover to emergency carrier supply is such that the disturbance to transmission will be less than 10 milliseconds. The effect on speech is not detectable.

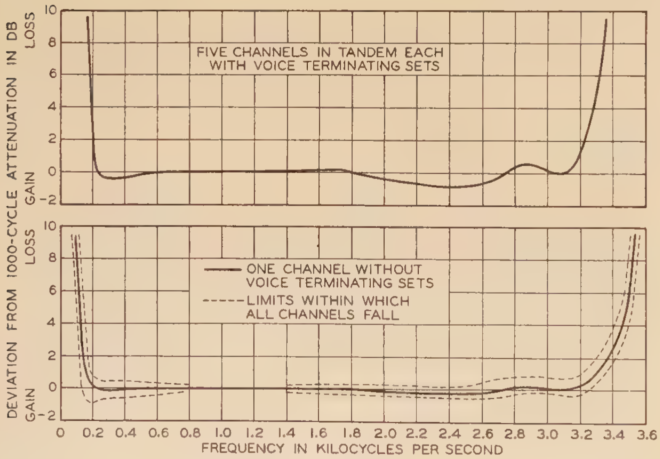

Figure 6. Channel frequency characteristic

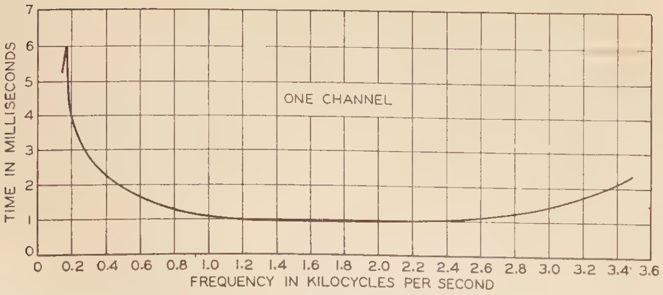

Figure 7. Delay characteristic

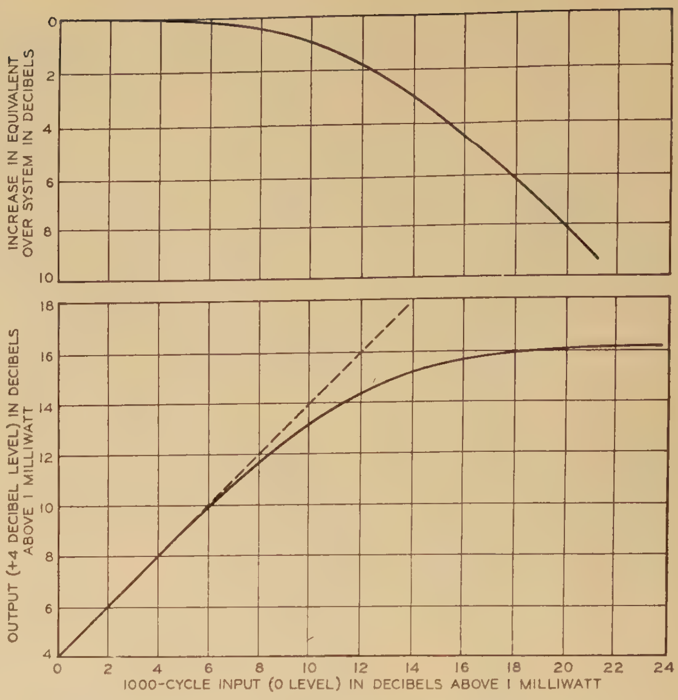

Figure 8. Channel load curve at 1,000 cycles

Maintenance Features

Since the type-*K* system provides more circuits in a group than ever before, it is essential that appropriately better maintenance facilities be furnished. Wherever vacuum tubes are used, jacks have been included to permit testing the condition of the tube by plugging in a new type of test set. The testing of a working tube with this set will not produce an appreciable reaction on performance of the circuits involved. When it has been determined that a tube in the common equipment is nearing the end of its useful life, a special transfer cord circuit is used to remove the circuit involving the tube from service and to substitute a spare circuit temporarily while the defective tube is replaced. This transfer from a regular to a spare and vice versa can be made without effect upon service.

In a type-*K* terminal office transmission tests are made at the four-wire test board shown in figure 9*A* where the incoming and outgoing voice-frequency circuits appear and at the high frequency test board shown in figure 9*B*. At the former, four-wire talking, monitoring and testing circuits have been provided for voice-frequency maintenance. Adjustment of the equivalents of the individual channels can be made from this point as previously described. Much can be done from this position by means of monitoring and noise measuring to diagnose troubles.

At the high-frequency testboard the circuits are brought

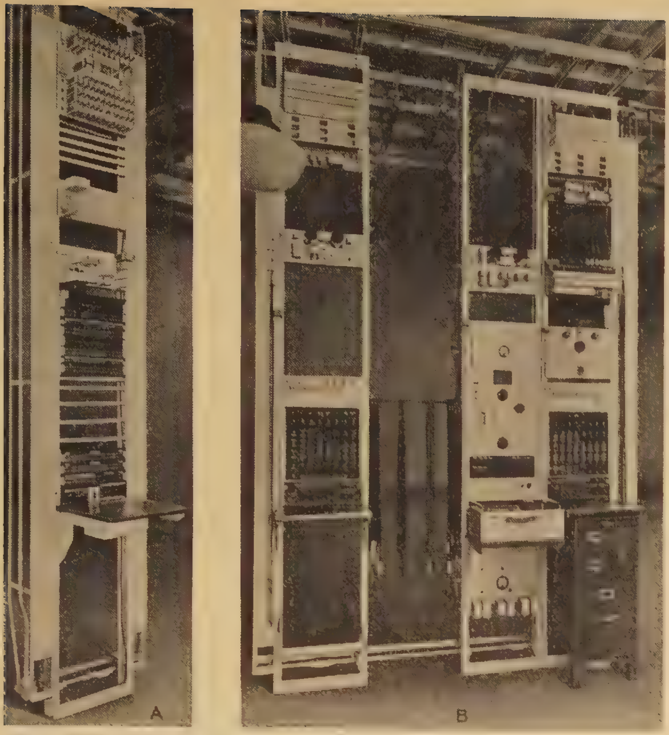

Figure 9. Test positions

A—Voice frequency *B*—High frequency

through jacks and high-frequency measuring apparatus is provided. Measurements can be made on operating systems to determine the performance of the intermediate repeaters and regulators with respect to level and equalization over the frequency range from 12 to 60 kilocycles. Loss and gain measurements also can be made either between this point and the voice-frequency four-wire test board, through the carrier terminal equipment or through the next adjacent repeater or terminal office at high frequencies. It is possible to test the high-frequency portion of the terminal and to substitute a spare, by patching or rapid transfer, for a defective or potentially defective group modulator, transmitting amplifier, group demodulator or receiving amplifier.

Some of the high-frequency testing equipment is shown mounted on the middle bay of figure 9*B*, of which one of the most important units is the 1- to 150-kilocycle test oscillator located at the center of this bay. It is a heterodyne type of oscillator which covers the frequency range with a continuous film strip scale about 300 inches long. Its maximum output is about one watt and this varies less than one decibel over the entire range. It is provided with built-in calibrating features and can be set to any frequency with an absolute accuracy of about 25 cycles. It is used as the tuning control of the pilot level measuring circuit. An auxiliary scale on the oscillator permits tuning the measuring circuit directly in terms of frequency.

The pilot-level measuring circuit is of the double heterodyne type and includes a copper-oxide modulator which is supplied with carrier from the heterodyne oscillator, an intermediate frequency 130-kilocycle crystal filter of 10 cycles band width, a high frequency amplifier for this frequency, a copper-oxide demodulator supplied with carrier from a 129-kilocycle fixed frequency oscillator, a voice-frequency amplifier, and calibrating circuit. The input impedance of the measuring circuit is high so that when it is bridged across a line pair at the high-frequency test-board jack fields it does not produce appreciable loss to the line. The circuit permits measuring each of the three pilot frequencies to check levels and equalization of operating systems. The panels comprising the circuit are shown below the oscillator in figure 9*B*.

Mounted on a shelf just below the oscillator is the transmission-measuring set which contains a highly accurate thermocouple and meter-combination with calibrating circuits, wide-range repeating coils, a test-key circuit, and attenuators, one of which can be set in steps of one decibel up to a total of 90 decibels.

Equipment Features

Because of the large number of systems likely to be terminated in an office, the jacks are concentrated in a group of bays located together for ease in patching and testing. There are in general five major divisions of the terminal equipment consisting of channel-modem bays, group-modem bays, carrier-supply bays, high-frequency test board, and four-wire voice-frequency patching board and associated voice terminating equipment. The general arrangement in an office is such as to simplify the cabling between various groups of equipment.

The cabling of a high-frequency jack bay, shown in fig-

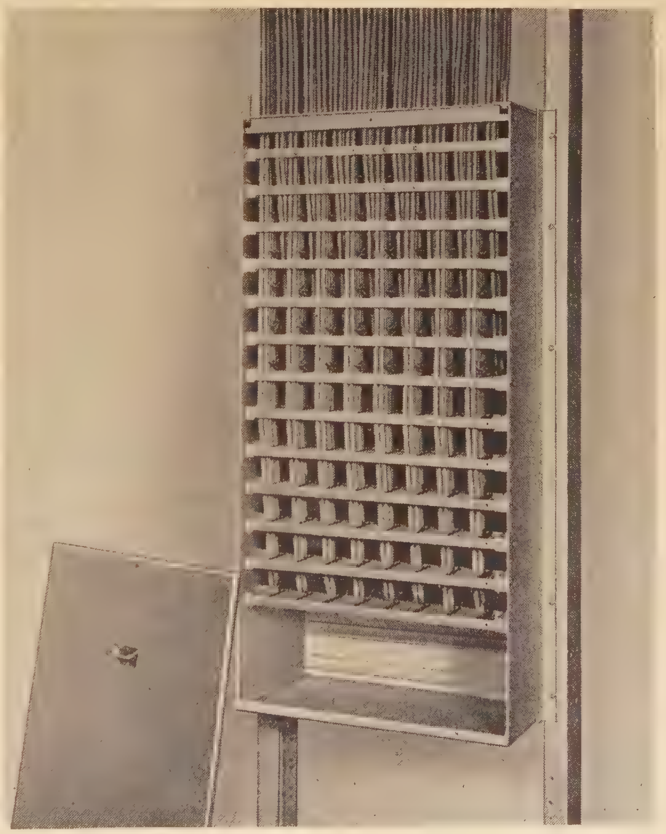

Figure 10. Cabling of high-frequency jack bay

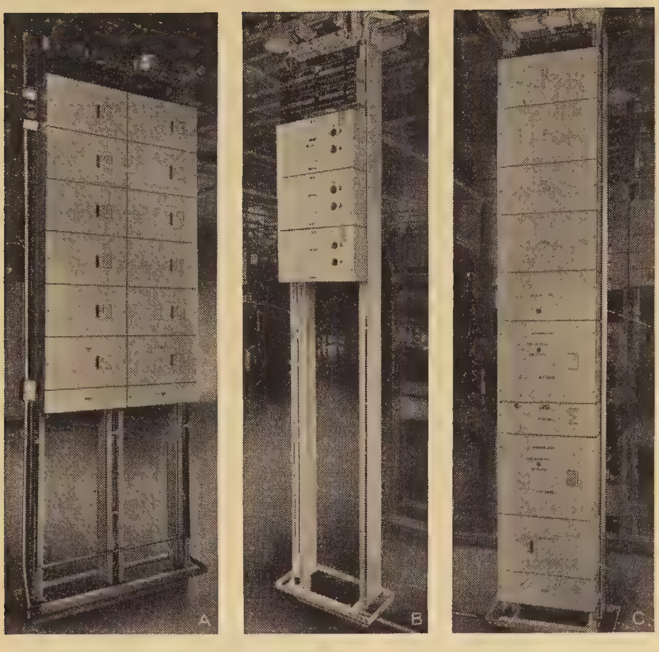

Figure 11. Carrier-equipment bays

A—Channel *B*—Group
C—Carrier and pilot supply

ure 10, illustrates the congested wiring condition occurring when a large number of heavy shielded wires is run to one location. Because of this congestion the jacks in this bay are mounted or removed from the front.

The concentration of equipment in the modem unit is made possible by the small size of the copper-oxide bridges and the filters. Figure 11*A* shows 12 modem units for two systems on adjacent bays with space left at the bottom for the six modems of a third system.

The group modems are about the same size as the channel modems and include a modulator, a demodulator, a transmitting amplifier, and auxiliary receiving amplifier with associated filters. Figure 11*B* shows three units for three systems with space for six additional units at the bottom of the bay.

The carrier supply equipment for ten systems is mounted in one bay as shown in figure 11*C*, which includes the regular and emergency generators, transfer unit distributing equipment and pilot channel supply panel. The bays of this type are located near their associated channel equipment because the supply is chiefly for channel modems. One carrier distributing unit provides for the even and another for the odd harmonics. All terminals and bus bars of these units which are common to the ten systems are protected by insulating covers.

The four-wire voice-frequency jacks for all the systems in an office will ordinarily be grouped in associated bays, one of which is shown on figure 9*A*. A bay will accommodate five systems as an average, that is, 60 voice circuits including the necessary pads and telephone set.

The high-frequency test board is an arrangement of sealed test terminals, high-frequency patching jacks and high-frequency testing equipment mounted on bays as shown in figure 9*B*. Only a few high-frequency patching jacks were required initially and these were therefore mounted above the sealed terminals. This arrangement of bays with the addition of a high-frequency patching bay at the right of each sealed terminal bay will accommodate 100 systems.

The carrier pairs are split off from the main toll cables at splices in the cable vault. The input circuits are carried thence in lead covered cable to the cable crosstalk balancing bays and thence to the input sealed terminal. The output pairs run directly from the output sealed test terminal to the splice in the cable vault. The remaining high frequency wiring from rack to rack is shielded wire.

Conclusion

The carrier-telephone terminals for the type-*K* system which have been described are simpler, occupy less space, and provide better transmission performance than multichannel carrier terminals used previously in the Bell System. As part of a general development of broad-band transmission systems, it is very desirable to employ equipment which can be used in common with several systems. The 12-channel bay, much of the carrier supply, and all of the voice-frequency terminating equipment of this type-*K* system terminal will be used to form corresponding parts of the terminals for the 12-channel open-wire system and the coaxial system, both of which are under development. This not only has simplified the development work, but also will result in greater mass production of these common parts and provide desired uniformity of voice-frequency terminating levels and maintenance arrangements.

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3. Carrier Telephone Systems for Toll Cables, **C. W. Green** and **E. I. Green.** Presented at the 1938 winter convention of the AIEE.

4. Crystal Channel Filters for the Cable Carrier System. **C. E. Lane.** Presented at the 1938 winter convention of the AIEE.

5. Magnetic Generation of a Group of Harmonics, **E. Peterson, J M. Manley,** and **L. R. Wrathall.** Electrical Engineering, August 1937.

Discussion

For discussion of this paper see page 259.

Crystal Channel Filters for the Cable Carrier System

By C. E. LANE
ASSOCIATE AIEE

SINCE the channel selecting filters used at the terminals of the 12-channel cable carrier system are the principal filters in the system this paper is concerned primarily with these filters. Their importance is evident from the fact that they represent over one-third of the cost of the system terminals.

Many new features appear in these channel filters. The most outstanding is the use as filter elements, along with inductance coils and condensers, of plates cut from crystalline quartz. It is for this reason they are called "crystal filters." In addition, however, the inductance coils, some of the condensers, and also the filter assemblies have in them new features. Only after a number of years of laboratory experimentation with filters using crystal elements, studying their advantages and limitations, was the cable carrier system planned to use such filters.

There are 12 channel filters which transmit the lower side bands derived from the modulation of the speech signals with carrier frequencies spaced four kilocycles apart from 64 to 108 kilocycles. An insertion loss frequency characteristic which applies for each of the 12 filters is shown in figure 1. Regarding a ten decibel loss increase as the cutoff as compared with transmission at 1,000 cycles, the voice-frequency band for a single carrier link, largely determined by the characteristics of the channel filters, extends from approximately 150 to 3,600 cycles. For five links the band extends from about 200 to 3,300 cycles. This is a 600 or 700 cycles wider frequency band than the present three-channel open-wire carrier system. The maximum delay distortion in the transmission band of each of the filters is about 0.4 millisecond. As many as ten of these filters may appear in tandem in the longest talking circuits. The total delay distortion in such cases would then not exceed 4 milliseconds. This is not objectionable since the average listener cannot observe the effect of delay distortion unless it exceeds about 10 milliseconds. A representative filter schematic is shown in figure 2. The condenser shown by the dotted line at the left is used only in the two lowest frequency filters to obtain an impedance transformation internal to the filters and thereby permit the use of crystals of practical thicknesses for these filters. However, the equivalent circuit for each of the 12 filters is the same. In the system the filters work in parallel at one end and between terminating impedances of 600 ohms. The two condensers appearing in the series arms at the left end of the filter schematic are used in obtaining satisfactory operation of the filters in parallel and otherwise might be omitted provided the inductance at this end was made smaller at the same time.

Figure 2 indicates the separate physical elements and the manner in which these are connected in the filters. In considering the performance of the filters the crystal elements are replaced by their equivalents, an inductance and capacitance in series, shunted by a second capacitance as shown in figure 3. Also, the condensers in shunt across the filter are shown inside the lattice combined with the direct capacitance of the crystals and the inductances are relocated in series in each lattice arm. In making this conversion, however, the effective resistance of the in-

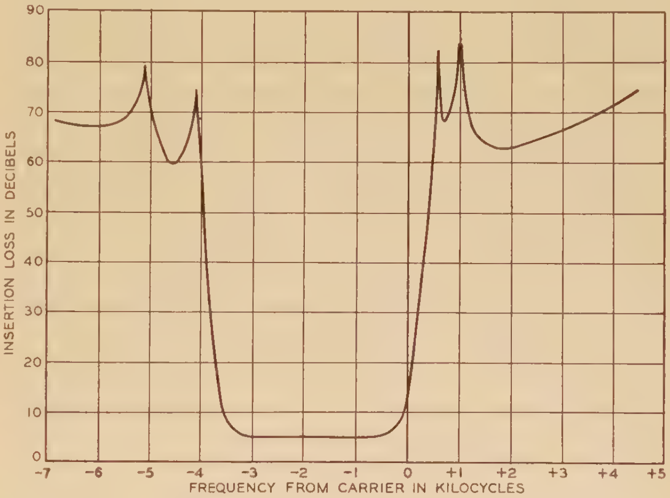

Figure 1. When plotted in cycles removed from the carrier frequency, the insertion loss frequency characteristics of each of the 12 crystal channel filters are for all practical purposes identical

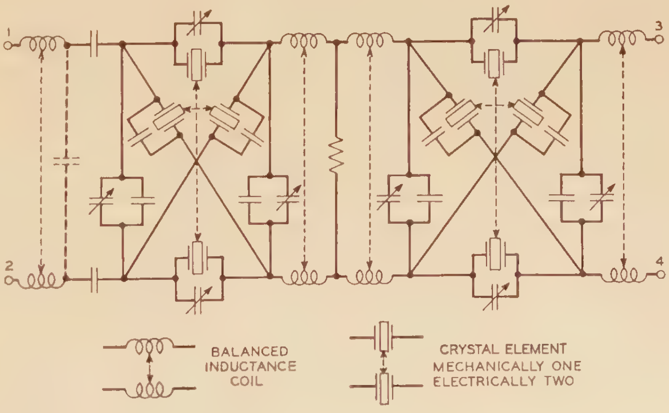

Figure 2. The schematic circuits of each of the 12 filters are the same except for the addition of the condenser shown by the dotted lines which appear only in the two lowest-frequency filters

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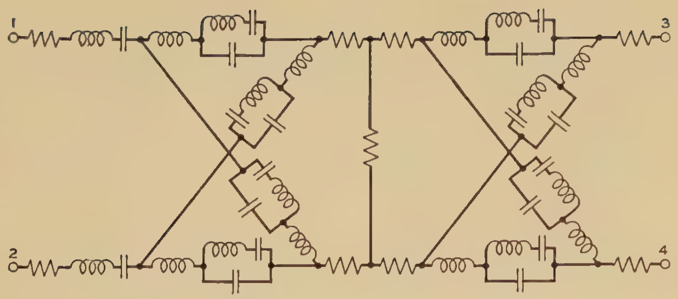

Figure 3. The schematic circuits of the filters are each equivalent to two lattice sections with a resistance pad between them, resistances at each end, and at the paralleling end a coil and condenser which resonate at the midband frequency

ductance coils are, for reasons which will appear later, shown remaining outside the lattice. Also the capacitances and the portion of the inductance which are used solely for purpose of paralleling are left outside the lattice. The basis for the conversion from figure 2 to figure 3 is shown in figure 4.

Before considering further the filter as a whole, the nature of the crystal elements themselves and the reason for using them will be considered. It is common knowledge to those familiar with the performance of electrical wave filters that the energy loss unavoidably associated with inductances imposes limitations upon the filter characteristics obtainable. Capacitances may be designed so that the energy dissipation is small and negligible as compared to that in the inductances. With ideal reactance elements entirely free from dissipation, filters might be designed for any band width with as little loss in the band as wanted and at the same time frequencies might be rejected outside the band by any amount desired, no matter how near such frequencies were to the edges of the transmitting band. Of course the sharper the filter cutoffs, other requirements being the same, the more complex the filter structure would be even neglecting dissipation. The greater the dissipation in the filter elements, the greater the loss in the transmitting range of the filters and the greater the number of cycles required for this loss to rise from the relatively low and uniform loss in the transmitting band to the high loss wanted outside the band. In the design of channel filters for carrier systems, the presence of dissipation in the filter elements is costly in that the channels must be spaced farther apart than would otherwise be necessary, thereby wasting frequency space. At the same time the loss to transmitted frequencies must be made up for by amplification. The amount of dissipation in a reactance element is measured by the ratio of the effective resistance component of its impedance to the reactance component at any frequency. The reciprocal of this ratio is called the Q of the reactance and hence is a measure of efficiency or freedom from dissipation. In the design of inductances in the form of wire-wound coils, it is generally not practical to obtain Q's much in excess of 200 or 300 at any frequency. The quartz crystal element used in the filters as previously stated is equivalent electrically to a two-terminal reactance consisting of an inductance and capacitance in series shunted by a second capacitance. For the Q of the inductance in the equivalent circuit of the crystal element a value of 15,000 or more can readily be obtained. It is for the purpose of utilizing this high Q inductance and obtaining the benefits therefrom that crystal elements are used in these filters.

The filter schematic in figure 2 shows crystal elements in each filter section; the two in the lattice arms and the two in the series arms in each case are identical. Electrically there are four crystals in each section but for reasons of economy and for convenience in handling and adjusting the crystals those in corresponding arms are physically one. This is possible since the filter is a balanced structure and the two like crystals vibrate in unison. Figure 5 is a photograph which shows a representative double crystal element taken from each of the 12 filters. The four crystals in the lowest-frequency filter range from 40.2 millimeters to 41.8 millimeters in length and those in the highest-frequency filter from 23.8 to 24.3 millimeters. The thickness of the crystals in all four of the lowest-frequency filters are 0.63 millimeters, in the next four filters 0.82 millimeters, and in the highest-frequency filters 1.1 millimeters. Uniformity in thickness is maintained as far as practicable since it contributes to economy in manufacture of the crystal. Within the range using the same crystal thickness the impedance and frequency differences, called for by the design of the different filters, can be provided by variations in width and length of the crystals. The ratio of width of the crystals to their length ranges from about $^1/_2$ to $^4/_5$.

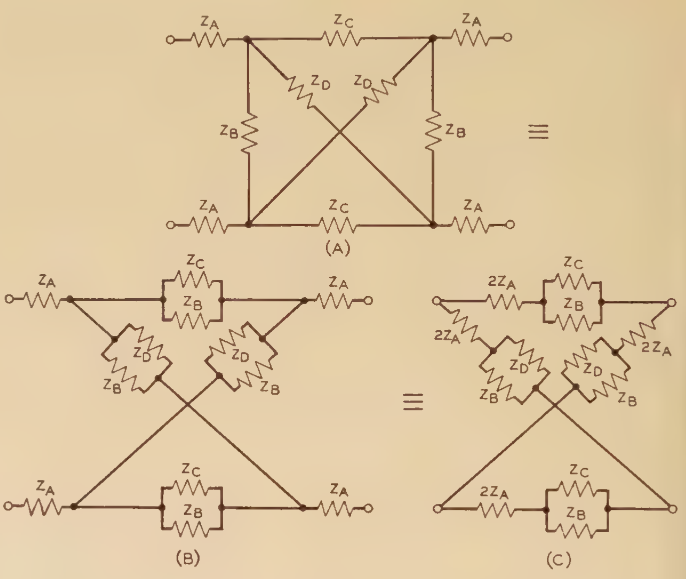

Figure 4. It does not alter the transmission properties of a network such as shown in figure 4A to remove the impedances in shunt and outside the lattice and replace them by impedances of equal magnitude in shunt across each lattice arm nor by removing the impedances in series with the lattice and replacing them by series impedances inside the lattice of twice the magnitude of those removed

The major surfaces of the crystals are plated with a thin layer of aluminum deposited by an evaporation process. This plating is divided along the center line lengthwise of the crystals to form the two electrically independent crystals. Since the crystals vibrate longitudinally with a node across the middle, they are clamped at this node in mounting. Figure 6 shows the orientation of the crystal plates with respect to the natural axes of the quartz from which they are cut. The plates are cut as accurately as practical to the dimensions computed making a small allowance in length and then the crystal is finally adjusted in an electrical circuit by grinding the end of the crystal until the resonant frequency falls within five or ten cycles of that desired.

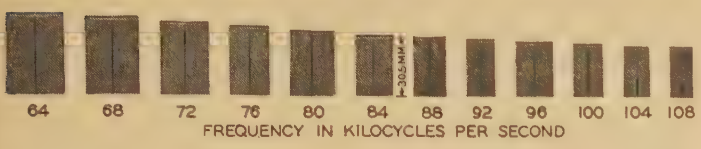

Figure 5. The length of the crystal elements used in the different filters varies about inversely as the frequency of the filter band location

Considering again the filter schematic as a whole, figure 3, and neglecting the dissipation in the crystals and condensers, the filter may be regarded as made of two lattice filter sections having ideal reactance elements, that is, elements free from dissipation. The location of the effective resistance of the coils outside the lattice, for purpose of performance analysis, shows, how, at the end of the filter these resistances may be regarded as part of the terminating impedance between which the filter works and how between the filter sections the resistances may be combined with a shunt resistance to form a resistance pad which matches the image impedance of the two filter sections. The effect, then, of the coil resistances is primarily to provide a flat loss over the entire frequency range and does not affect appreciably the shape of the loss characteristic furnished by the reactance inside the lattice sections.

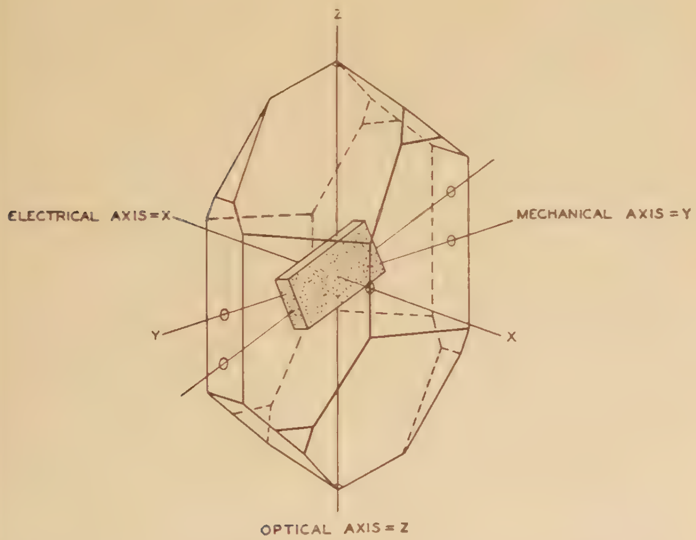

Figure 6. The crystal elements are cut with their major surfaces perpendicular to the electrical axis of the natural quartz, with their side surfaces making a small angle with the mechanical axis, and with their end surfaces making a small angle with the optical axis

In considering the performance of lattice-type filter sections, it is common practice to sketch together the frequency reactance curve of the two lattice arms Z_x and Z_y. This is done for one of the filter sections and is shown in figure 7. In the frequency range where the two curves are of opposite sign the filter transmits and where they are of the same sign there is attenuation. At the point where the two curves intersect there are attenuation peaks of very high loss. The reactance curves of figure 7 are for the filter section accountable for the pair of attenuation peaks shown in the filter characteristic which are the closer to the edges of the transmitted band. For the other section the cross-over points of the two reactance curves are farther away from the band, since this section is responsible for the outer pair of attenuation peaks. The design of the filters consisted in determining values for the inductance coils, condensers, and crystals, such that the reactance curves of the lattice arms of the filter passed through infinity and intersect with each other at the desired frequencies and, at the same time, of determining the impedance level for all of the elements such that the filters would have the right image impedances.

The curves of figure 7 would seem to indicate a somewhat greater band width for these filters than shown by the insertion loss characteristic of figure 1. The reason

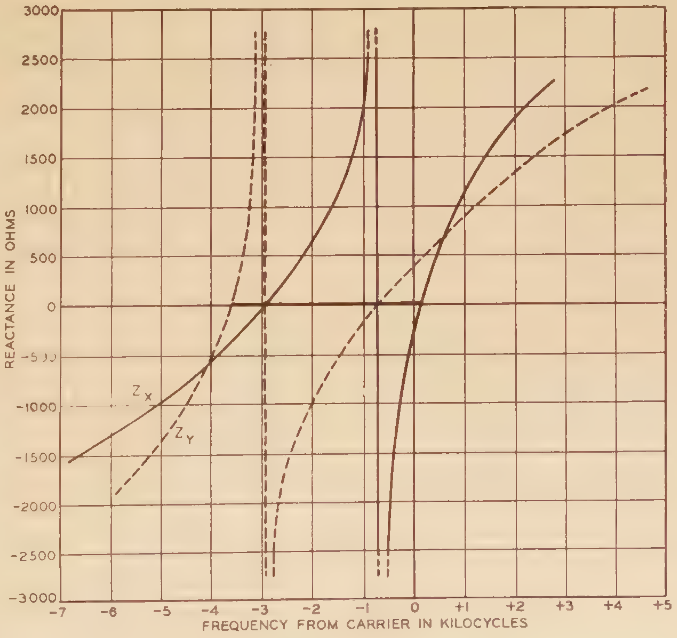

Figure 7. In a lattice filter section transmission occurs for frequencies where the impedances for the two arms of the lattice are of opposite sign and attenuation peaks of very high loss occur where the impedances cross

for this can best be explained by referring to the image impedance of one of the filter sections as shown in figure 8. Within the band the image impedance is, of course, a pure resistance which varies with frequency. It is about 800 ohms at midband frequency and falls rapidly to zero near the edges of the band. Assuming the effective resistance of the coils which is about 100 ohms as belonging to the terminating impedances, the filter sections actually work between impedances of about 700 ohms. This means that large reflection losses occur at each end of each filter section near the edges of the transmission band where the image impedance of the filter is very small. It is these reflection losses that are responsible for the actual transmission band being much narrower than it would be with the filter sections terminated in their actual image impedances. The filter sections are designed with 800 ohms image impedance at midband frequency instead of 700 ohms to make the band flatter and somewhat wider than it would be otherwise.

When a number of band filters are operated in parallel it is generally necessary to connect across the paralleled end a two terminal network to correct for the distortion that would otherwise be present in the highest- and lowest-frequency filters in the group. A circuit of the network used for this purpose with the channel filters is shown in figure 9.

The filters employ crystal elements in order to obtain abrupt discrimination between wanted and unwanted frequencies and at the same time to secure low and uniform loss in their transmitting bands. This characteristic must not only be obtained at the time the filters are assembled and adjusted but must be maintained throughout the service life of the filters and not appreciably affected by temperature variations. This imposes severe stability requirements upon the elements used in the filters. The crystal elements themselves are very stable when properly designed and once adjusted will retain at a given temperature their frequencies of resonance within one or two cycles seemingly indefinitely. Their temperature coefficient is only about 25 parts per million per degree centigrade which is not objectionable. The obtaining of suitable inductance coils and condensers for use in conjunction with the crystals that were adequate in stability required considerable development effort. The inductance coils were required to have not only a high degree of stability with respect to temperature and time but also a high ratio of reactance to effective resistance, low modulation, and at the same time be small in size. Air-core coils might have been designed for the purpose but they would have been quite large. The coils used are of the toroidal type wound on about one and three-fourths inch rings of molybdenum-permalloy. To reduce eddy-current losses the cores are made of very fine powder and then annealed to reduce hysteresis losses. The particles are mixed with insulating material and formed into rings by extremely high pressure. The inductance of the coils has a temperature coefficient of less than 40 parts per million per degree centigrade. The cores of the coils for the higher-frequency filters are wound with finely stranded wire to help secure good Q's (about 225). Because of the high impedance of the coils called for by the filter design, care is taken to make the capacity between the windings and the core and between the windings and the case as low as practical and also to make stable all such small capacities as must be present.

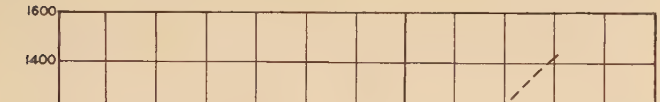

Figure 8. The large reflection losses occurring within the transmission band of the filters and near the edges of this band has the effect of narrowing the width of the transmission band

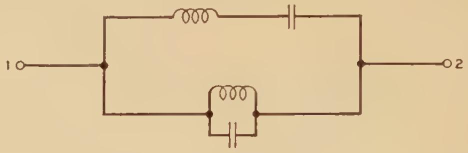

Figure 9. A two-terminal reactance network is connected in shunt across the filters at their paralleling end to improve the characteristic of the highest- and lowest-frequency filters

The two extra condensers used at one end of each filter for paralleling purposes are of a high-grade mica type. The other condensers are all quite special. The fixed ones, ranging in magnitude from about seven micromicrofarads to 100 micromicrofarads are made by plating short lengths of high-grade glass tubing inside and outside with silver. Because of the intimate association of electrodes with the surfaces of the tubes and the low expansion coefficient of the glass used a condenser is obtained that has a temperature coefficient comparable with that of the coils and crystals. No aging effect has been observed. It will be noticed that four small adjustable air condensers appear in each filter section. These are used to secure precise initial adjustment of the filter capacitances.

To protect the filter elements against moisture, the filters are hermetically sealed in a container made from a rectangular section of seamless brass tubing with closely fitting plates soldered in each end. One end plate carries four metal-glass seal terminals and a nozzle through which dry air is blown after the filter is assembled. The other end plate is provided with a small hole for the escape of the drying air. After the drying operation the hole in the nozzle and the hole in the opposite end of the filter are closed by soldering. The elements that make up the filter are assembled on a chassis which is completely wired and then slid into the container in assembly. Figure 10 is a photograph showing this chassis and the arrangement of the elements. The elements are located in such a way as to use very short wiring connections which reduce the magnitude of any stray admittances. The wired filter chassis is carefully adjusted by setting the values of the air condenser such that for each filter section the resonance frequencies looking into each end of each section occur where they theoretically should. This compensates for the effect of small capacitances between the filter parts. In the design of the filter parts care is taken to use no material which absorbs moisture readily since such moisture would later be released and raise the relative humidity of the air inside the filter.

If voltages much in excess of about 20 volts are applied across crystal elements at frequencies near resonance, the crystals will break from the mechanical strain of their vibration. The maximum safe voltage across the channel filters at the resonant frequencies of the crystals in them is considerably greater since at resonance the full voltage does not appear across the crystals. In their normal use in the system the voltages across the filters will be very much less than 20 volts.

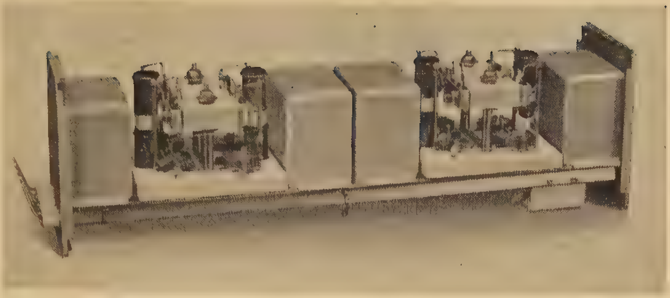

Figure 10. The filter parts are assembled and wired on a chassis which is slid as a unit inside the filter container

Other filters forming part of the terminal apparatus are the group modulator and group demodulator low-pass filters, the channel and group carrier supply filters, and the pilot supply filters. The group modulator and demodulator filters are of the low-pass type employing only coils and condensers as elements. The group carrier supply filter is the same in schematic and mechanical design as the crystal channel filters described. The pilot supply filters and the channel carrier supply filters are equivalent in schematic to one section of the channel filters. Mechanically, of course, they are only about half the size and are hermetically sealed in the same manner.

References

For a further discussion of crystal filters the reader is referred to THE EVOLUTION OF THE CRYSTAL WAVE FILTER, O. E. Buckley, *Journal of Applied Physics*, October 1936, and ELECTRICAL WAVE FILTERS EMPLOYING QUARTZ CRYSTALS AS ELEMENTS, W. P. Mason, *Bell System Technical Journal*, July 1934.

Discussion

For discussion of this paper see page 259.

Crosstalk and Noise Features of Cable Carrier-Telephone System

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CROSSTALK and noise are important factors in cable carrier transmission as outlined in the paper "A Carrier Telephone System for Toll Cables" by Messrs. C. W. Green and E. I. Green. Crosstalk and noise limit the number of carrier channels which can be utilized in any one cable, not only by limiting the number of channels which can be placed on a single pair, but by limiting the number of pairs which can be used. Noise also controls the transmission loss which can be permitted between repeaters. Without the crosstalk and noise reduction measures described in this paper, the number of carrier channels per cable would be so few and the spacing between repeaters so short, that the type-*K* carrier system would be impracticable.

Crosstalk

To utilize existing toll cables in the Bell System for frequencies up to 60 kilocycles required the solution of many new crosstalk problems because: (1) crosstalk increases rapidly with the frequency; (2) nonloaded carrier pairs due to their high speed of propagation are especially suitable for very long distances and hence the crosstalk requirements per unit length are relatively severe; (3) the large gains of the carrier repeaters amplify certain crosstalk currents much more than in the case of voice frequency circuits.

Two general effects need to be considered: intelligible crosstalk must be prevented; and a large number of circuits crosstalking into a particular circuit must not contribute an undue amount of noise. The second effect is called babble, since it consists of a multiplicity of unrelated voice sounds which, in the aggregate, are unintelligible.

An important feature is the use of different cables for opposite directions of transmission. This makes the major crosstalk problem the reduction of crosstalk between pairs in the same cable used for transmission in the same direction. The crosstalk currents due to transmission at one end of a disturbing circuit through the distributed couplings with a disturbed circuit tend to arrive at the distant end at the same time since the currents via any of the couplings travel substantially the same distance. This makes it possible to greatly reduce the total effect of these distributed couplings by the use of small adjustable mutual inductance coils connected between pairs at one point in each repeater section.

If nothing more were done, there would still be objectionable crosstalk since currents from the outputs of carrier repeaters could crosstalk into voice-frequency circuits and these circuits could then again crosstalk into other carrier-frequency circuits at points near their repeater inputs. This effect is minimized by transposing the carrier pairs from one cable to the other at carrier repeater points.

At common voice-frequency and carrier-frequency repeater points there would be an unsatisfactory crosstalk path from a carrier repeater output into all the wires not used for carrier frequencies and from them through coupling between office wiring into similar wires in the other cable and finally into carrier repeater inputs in the second cable. This crosstalk is minimized by the use of carrier-frequency suppression coils in the voice-frequency circuits. These coils also serve the purpose of preventing carrier frequency noise originating in voice frequency circuits from being transmitted into the cables and inducing noise at points near carrier repeater inputs.

NEAR-END CROSSTALK

Near-end crosstalk is the result of coupling between circuits transmitting in opposite directions, while far-end crosstalk is the result of coupling between circuits transmitting in the same direction. Near-end crosstalk coupling between different carrier circuits of the same frequency must be kept very small, particularly near a repeater point, since crosstalk from the output of a repeater into an opposite directional pair near the input of its repeater will be greatly amplified by this repeater.

Crosstalk between carrier circuits within the offices is kept low by careful shielding, segregation, suppression of spurious paths through battery supply, common grounding arrangements, etc.

Since the type-*K* system operates on a "four wire" basis, different electrical paths are used for opposite directions of transmission. Satisfactory near-end coupling in the outside plant is obtained, therefore by placing east bound pairs in one cable and west bound pairs in another. When two cables have relatively heavy sheaths as in the larger Bell System cables, their coupling is sufficiently small even with the two cables in close proximity.

INTERACTION CROSSTALK

The crosstalk currents from a carrier repeater output into voice-frequency circuits in the same cable must be limited, since they crosstalk again into carrier circuits near repeater inputs and, consequently, are amplified by the high-gain repeaters. Intermediate circuits most responsible for crosstalk of this type are made up of combinations of pairs and phantoms and the sheath, i.e., longitudinal paths.

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1. For all numbered references, see list at end of paper.

One case of crosstalk of this kind would occur if the same cable were used for carrier pairs transmitting in the same direction on both sides of a repeater. This is prevented by transposing carrier pairs from one cable to the other at each repeater point, as shown on figure 1.

A second interaction crosstalk problem is encountered at the common voice and carrier repeater points and involves coupling between cables as well as in the same cable. Here the coupling path is from carrier repeater outputs to intermediate circuits in the same outside cable, back into the common office over these intermediate circuits and then via office coupling to intermediate circuits in a second outside cable and from there to carrier repeater inputs connected to pairs in the second cable. Referring to figure 1, a set of noise (and crosstalk) suppression coils is encountered in this path. The high longitudinal circuit impedance of these coils minimizes this interaction crosstalk.

Far-End Crosstalk

Far-end crosstalk currents are subjected to line attenuation and amplification similarly to the main transmission currents, and do not have extra amplification as in the case of near-end crosstalk. Furthermore, far-end crosstalk currents due to couplings at different points along the line tend to arrive at the distant end of the disturbed circuit at the same time. Hence a considerable portion of the far-end crosstalk over the type-K frequency range, which occurs between circuits transmitting in the same direction in the same cable, can be neutralized by introducing compensating unbalances at only a comparatively few points, such as one per repeater section. The far-end crosstalk reduction problem is greatly simplified because phantom circuits are not used for carrier operation.

Theoretically, for the same precision of match between the impedances in the two directions at the balancing point, the crosstalk reduction would be about the same whether the balancing is done at an intermediate point or at either end of a repeater section. Balancing will be done at repeater inputs rather than at an intermediate point, such as the middle, because it is practicable to obtain repeater impedances matching the average line impedance sufficiently well so that the effectiveness of balancing is reduced only slightly.

Nature of Far-End Crosstalk Coupling

The coupling between two cable pairs in a short length may be represented by a mutual admittance and a mutual impedance. The former is due almost entirely to capacitance unbalance, which varies but little with frequency, so that its effect could be practically balanced out by means of a simple condenser. The latter, however, involves a complex mutual inductance of the form $M_a + j\,M_b$, because of the proximity effect of the wires of a pair and of other cable conductors.[1] As shown on figure 2, both components vary considerably with frequency; M_a on the average decreasing as the frequency increases while M_b in the general case is of negative sign and reaches a maximum value at 56 kilocycles.

Type of Balancing

To obtain maximum reduction in crosstalk it would be necessary to use a condenser for balancing the mutual admittance and an inductance coil for balancing the

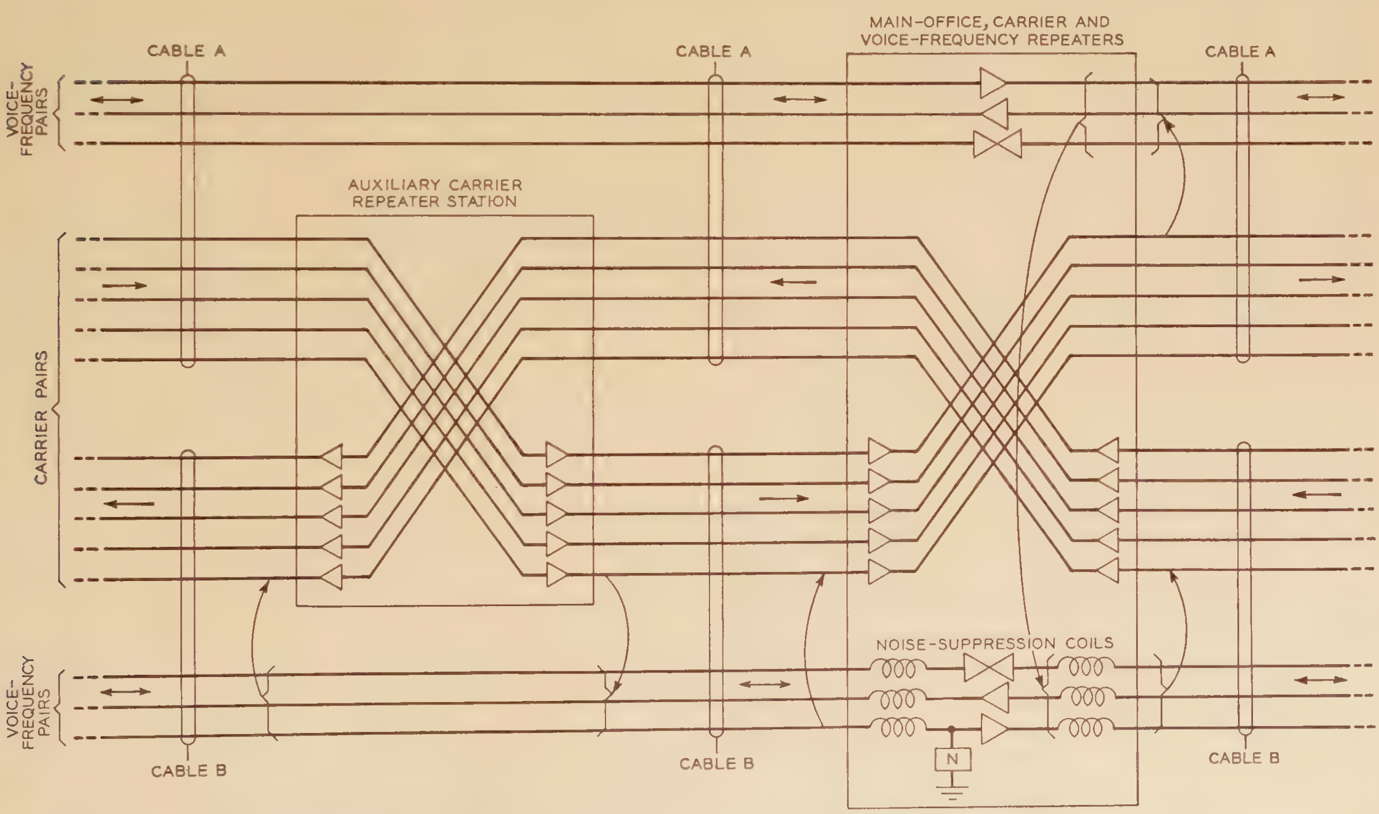


Figure 1. Schematic showing carrier pairs transposed between cables, coupling paths and noise suppression coils

mutual impedance or to use some equivalent complex network. Experimental balancing in a particular cable using the coil-condenser method reduced the mean crosstalk over the type-K range about 20 decibels, which is close to the maximum reduction possible with a universal type of balancing unit. The reduction is limited by the fact that two pairs having identical crosstalk couplings in each of two short lengths at different points in the cable will not produce two identical elements of crosstalk current at a circuit terminal because: (1) Cable circuits are not perfectly smooth. Reflections, as at junctions of reel lengths or at terminals, alter the two crosstalk currents differently. (2) The propagation constants of each circuit vary slightly from reel to reel in a random fashion and therefore the two crosstalk currents are of slightly different phase and magnitude. (3) In any short length the disturbing circuit produces crosstalk currents in intermediate circuits, which are propagated along these circuits and crosstalk again into the disturbed circuit at various points, producing an additional crosstalk current at the circuit terminal. At any frequency, this interaction crosstalk current has a random phase and magnitude relation to the crosstalk current for the short length considered by itself, and depends also upon the position in a repeater section of the short length.

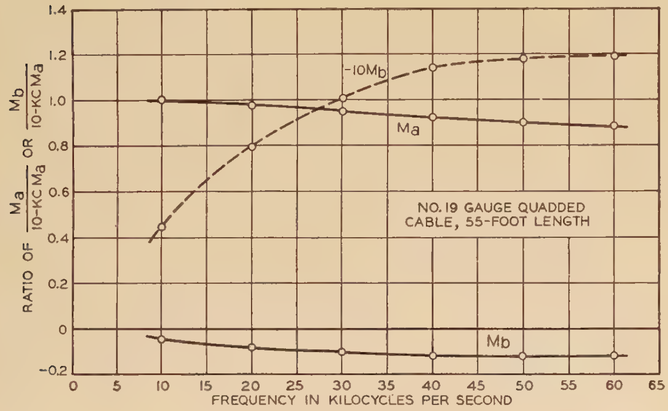


Figure 2. **Mutual inductance between cable pairs in terms of value for M_a at ten kilocycles**

A 20-decibel crosstalk reduction is not required, considering the number of K systems anticipated in any one cable. Studies were made, therefore, to determine whether satisfactory results could be obtained with a less expensive type of balancing, as outlined below.

The effects of frequency and circuit impedance on crosstalk coupling are as follows: (1) Crosstalk in a short length due to capacitance and to inductance coupling increases about directly as the frequency increases for circuits whose impedance is independent of frequency. (2) Crosstalk due to capacitance coupling varies directly as the impedance of the circuits while that due to inductance coupling varies inversely as the impedance. Changing the impedance from about 800 ohms for loaded voice circuits to about 135 ohms for nonloaded carrier circuits and changing the frequency from about four kilocycles to 60 kilocycles increases the crosstalk due to capacitance coupling by a factor of about 2.5 and that due to inductance coupling by a factor of about 90.

Capacitive coupling in existing cables was reduced by design to as great a degree as practicable, particularly for the most closely associated circuits, because it is of most importance in the loaded voice frequency case. These same design measures also reduce inductive coupling but not to the same extent. Capacitive coupling decreases rapidly with separation due to the shielding effect of copper in intervening circuits while inductive coupling is not much affected by intervening copper wires. To minimize magnetic coupling it is necessary to use different lengths of twist for the pairs. Existing cables have relatively few lengths of pair twists.

As the net result, capacitance coupling is no longer all important, inductance coupling at 60 kilocycles actually predominating by a factor of about three to one in existing cables. Capacitance balancing should, therefore, be less effective than balancing designed to reduce the inductance coupling. Tests have shown that capacitance balancing alone gives a crosstalk reduction of about 11 decibels while inductance balancing alone gives a reduction of about 16 decibels. Since the latter reduction is sufficient, except possibly for small cables or special cases, the type-K balancing has been designed on this basis. Far-end crosstalk currents due to the two kinds of coupling have phase relations not differing from zero or 180 degrees by more than about 15 to 40 degrees, depending on whether the upper or lower type-K frequencies are considered. There is, therefore, a tendency for either type of balancing unit to annul both kinds of coupling.

To obtain as much as 16 decibels reduction it is necessary that the frequency characteristic of the balancing coil simulate that of the cable (figure 2). This was found practicable, as discussed later, by shunting the primary (or secondary) of the coil by a properly designed impedance.

Size of Balancing Coil

To meet the crosstalk requirement it is necessary to balance each carrier pair against every other carrier pair. If 50 carrier pairs were used, there would be 49 balancing coils connected to each pair for balancing to all the other

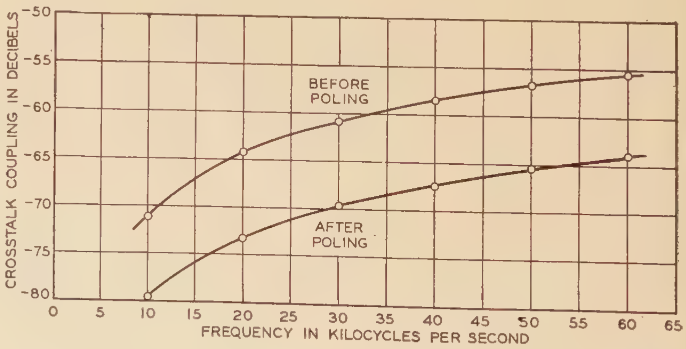


Figure 3. **Root-mean-square side-to-side far-end crosstalk per repeater section from measurements on 14 repeater sections**

pairs, a total of 1,225 coils. For convenience, adjustable coils having the same mutual-inductance range and the same self-inductance are used. Hence, the insertion loss per coil, resulting from the self-inductance and resistance of the coils, must be kept small. In addition, the self-inductance of the coil presents a problem from the impedance standpoint. To keep the impedance at any point in the balancing panel as nearly like the average cable impedance as practicable, the self-inductance of a series of coils must be neutralized by capacitances shunted at suitable intervals. It is very desirable, therefore, to use coils whose self- and mutual-inductances are no larger than actually essential. Consequently, an attempt has been made to keep the maximum crosstalk before balancing low.

Due to special measures, described below, it appeared that the maximum inductance unbalance per repeater section could be kept below about 1.3 to 1.5 microhenries, with the possible exception of side-to-side unbalances, and trial balancing coils were designed accordingly.

CROSSTALK REDUCTION BEFORE BALANCING

Changes in the original splicing are made at approximately 6,000-foot intervals, i.e., at points where voice-frequency loading coils must be removed from the carrier pairs. In most existing voice-frequency toll cables the 19-gauge quads were spliced as three groups, one, a two-wire circuit group, one, an eastbound four-wire circuit group, and the third, a westbound four-wire circuit group. Ordinarily, the carrier pairs will be selected from the four-wire groups because these groups are usually larger than the two-wire group and since the quads within a group are spliced at random there is less chance of a large value of coupling between pairs of different quads, i.e., two pairs are less apt to be recurrently in a relation of high coupling. The carrier pairs are divided evenly between the two four-wire groups, in order that the least number of four-wire voice circuits will be lost.

In cables with large four-wire groups it is satisfactory to maintain the grouping arrangement on the pairs converted to carrier. In such cables, however, one four-wire group is in the center or core of the cable and the other group in the outer periphery. In order that all circuits will have about the same velocity and attenuation and be subjected to about the same temperature conditions for both transmission and crosstalk reasons, one (four-wire) carrier group in these cables will be spliced to the other (four-wire) carrier group and vice versa at the 6,000-foot intervals.

In cables with relatively small four-wire groups, there is more chance of two pairs being recurrently in a relation of high coupling. To reduce this chance, a special splicing arrangement has been devised for use at the 6,000-foot intervals. With existing splicing the maximum coupling in cables with small groups is about 2.5 times that for cables with large groups. This ratio is appreciably reduced by the special splicing, likewise reducing the maximum mutual inductance that must be supplied by the balancing unit.

The foregoing was with particular reference to crosstalk between pairs in different quads. Crosstalk between pairs in the same quad (side-to-side crosstalk) is an additional problem. A quad consists of two twisted pairs of wires which are twisted together to permit the use of voice-frequency phantom circuits. Since the two sides of a quad are so closely associated, side-to-side crosstalk is generally much greater than that between pairs of different quads. The electrical size of the balancing unit, therefore, is determined by the side-to-side crosstalk, which is reduced by "poling."

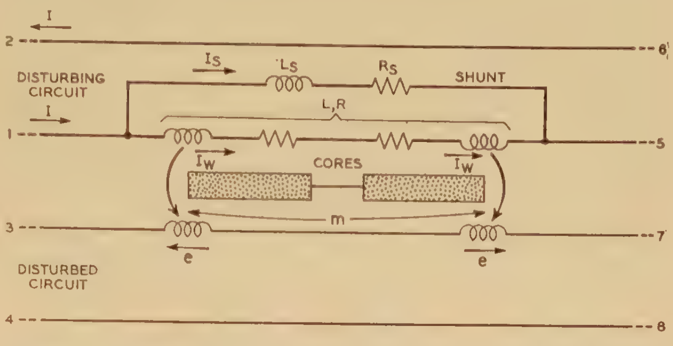


Figure 4. Schematic of a simple balancing coil designed to produce a complex mutual impedance

To apply poling, the quads are carried through as quads for an entire carrier repeater section. From measurements of side-to-side crosstalk in phase and magnitude, quads in one half repeater section are chosen and spliced to quads in the other half in such manner as to partially neutralize the side-to-side crosstalk. In effect, quads in one half-section serve as balancing units for the other half.

In most existing toll cables the side-to-side capacitance coupling was reduced when the cables were installed, by means of test-splicing within the 6,000-foot sections. Obviously, for poling to be effective it is necessary to operate mainly on the inductance component. The poling measurements, therefore, are made at about one kilocycle where an approximate measure of the inductance component can be obtained directly since the capacitance and inductance components of the crosstalk are at an angle of almost 90 degrees at this frequency. Figure 3 shows the crosstalk results obtained by means of one-kilocycle poling on 14 repeater sections. It has been shown that this 9-decibel reduction is within two to three decibels of the maximum reduction possible with much more complicated poling involving measurement and consideration of both components at carrier frequencies.

After side-to-side poling, coil balancing cannot be expected to give as much as 16 decibels reduction in crosstalk. This is unimportant, however, as long as the required reduction can be obtained more economically by the combined methods rather than by balancing alone.

CROSSTALK BALANCING COIL

Since the voltage which causes the crosstalk current in the disturbed circuit may be in either a clockwise or counterclockwise direction, the balancing device, for flexibility reasons, should be capable of establishing voltages in either direction. A balancing coil was developed, therefore, which in operation may be likened to that of two separate transformers with simultaneously movable cores. The primary windings are in series, as are the secondary windings, and are connected as shown in figure 4, for example. The relative direction of each secondary winding is the same, whereas the relative directions of the primary windings are reversed. With the cores in mid-position, the voltages induced in the two secondaries are equal in magnitude but opposite in phase, and the net induced voltage in the disturbed circuit is zero. As the cores are moved toward the left the respective components of the voltage induced in circuit 3-7-8-4 increase in a counterclockwise direction and decrease in a clockwise direction, the net result being a voltage in a counterclockwise direction. Such a setting of the balancing coil would be used to counteract a clockwise crosstalk voltage, the amount of departure of the cores from mid-position being dependent on the magnitude of the crosstalk voltage being counteracted. Movement of the cores toward the right produces the opposite effect.

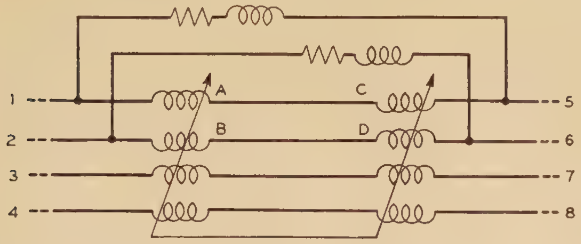


Figure 5. Schematic of winding arrangement of trial balancing coil

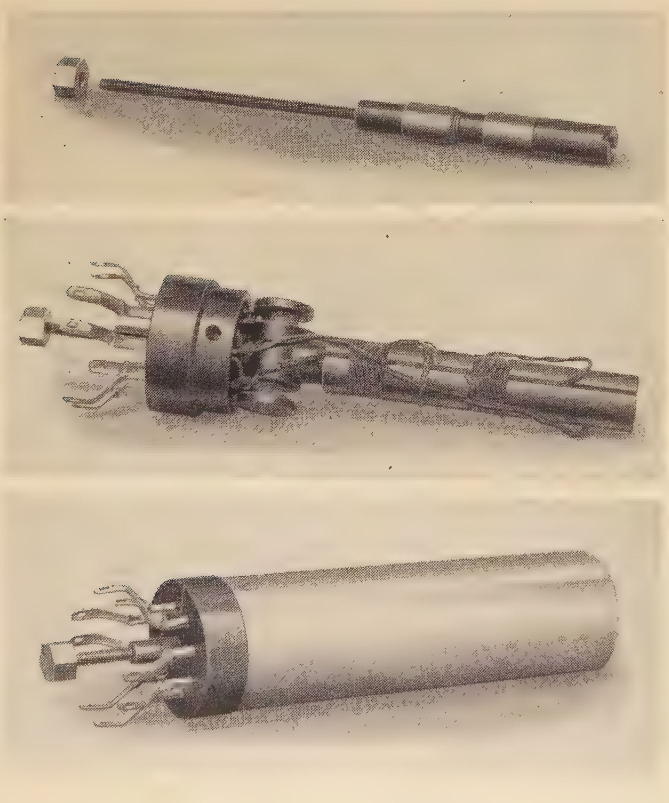
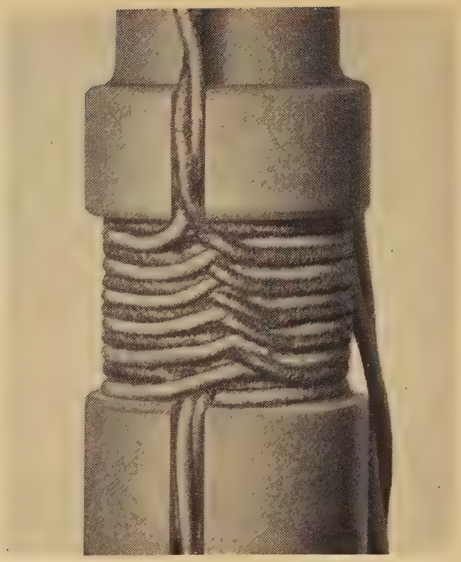


Figure 6. Trial balancing coil construction. Container is four and one-half inches in length and one and three-eighths inches in diameter

Figure 7. Arrangement of inner winding of trial balancing coil



This device, disregarding any proximity effects therein and the effects of the shunt, acts to set up a net voltage e which is in phase quadrature with the disturbing current I. Hence,

$$e = -j\omega m I \tag{1}$$

in which m is the net mutual inductance of the device. To obtain the required mutual impedance characteristic, the primary (or secondary) windings of the coil are shunted by an inductive resistance. Let the effective self-inductance and resistance of the line windings (primaries) be denoted by L and R, respectively, and the current through these windings by I_w. Let the effective self-inductance and resistance of the shunt be denoted by L_s and R_s, respectively. At balance, that is, when no crosstalk current flows in 3-7-8-4 due to I (the disturbing current), the current I_w is

$$I_w = \left[\frac{R_s(R + R_s) + \omega^2 L_s(L + L_s)}{(R + R_s)^2 + \omega^2(L + L_s)^2} - j\frac{\omega(R_s L - R L_s)}{(R + R_s)^2 + \omega^2(L + L_s)^2}\right] I \tag{2}$$

$$= [a - jb]\, I \tag{3}$$

where a and b are, respectively, the coefficients of the real and imaginary parts of the expression. Hence, with a shunted coil the voltage induced in the disturbed circuit is:

$$e = -j\omega m I_w = -j\omega(ma - jmb)\, I \tag{4}$$

The mutual impedance, Z_m, equals $j\omega(ma - jmb)$, or the effective mutual inductance M of the balancing coil may be written

$$M = M_a + jM_b \tag{5}$$

wherein $M_a = ma$ and $M_b = -mb$. Assuming R, L,

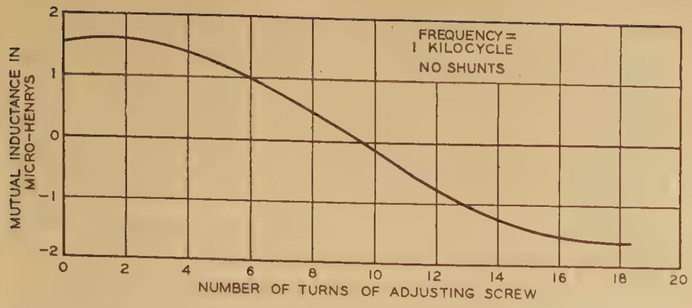


Figure 8. Mutual inductance of trial balancing coil

L_s, and R_s to be constant with respect to frequency of current and position of the cores, it is seen from (2) and (5) that for any core setting, M_a and M_b are functions of frequency only and their ratio at a given frequency is theoretically constant throughout the operating range.

To keep inductance L constant irrespective of the mutual inductance settings, the length of the coil windings, the length of the magnetic cores, and their spacings with respect to the winding spacing are so related that the change in inductance of one primary (or secondary) winding caused by motion of its associated core is equal and opposite to the change caused by the movement of the core associated with the other primary (or secondary) winding. To keep R low over the type-K frequency range, cores of finely powdered molybdenum permalloy pressed into a cylindrical form are used.

Because of other requirements which a balancing coil must satisfy, the winding arrangement actually employed is shown in figure 5. The simple device of figure 4 is not balanced from the standpoint of longitudinal crosstalk for any coil setting except that of zero mutual inductance. The figure 5 arrangement is such that theoretically there is no magnetic coupling between the two circuits for longitudinal currents in either one, regardless of the coil setting. Unless the capacitance between primary and secondary windings can be kept very small, the resultant admittance unbalance produces crosstalk which is not completely balanced out when the coil is adjusted. The turns of conductor in the figure 5 coil are so located that this side-to-side capacitance unbalance is less than five micromicrofarads. The capacitances between wires of either the primary or secondary winding do not affect the unbalance but contribute a part of the capacitance loading which compensates for the line inductance of the coils.

In the actual balancing coil, shown in figure 6, the windings are located in channels cut in a fiber tube which is secured to a head carrying the winding terminals and a bushing through which passes the threaded brass rod supporting the two cores. Below the head are small spool forms on which the shunts are wound. Insulating material such as bakelite is used to obtain proper spacing of the two cores.

The rather unusual manner in which the turns are applied is illustrated in figure 7, which is a close-up view of the two wires forming the inner winding. These two wires alternately cross over each other, progressing along the axis in opposite directions of rotation. The outer winding is similarly applied. This type of winding eliminates all splices within the coil, removing hazards incident to interior splices.

The complete coil assembly is enclosed by an aluminum container which serves the dual purpose of a shield and a convenient means of holding the coil for mounting purposes as this container fits snugly into an aluminum cup riveted to the assembly panel. The windings are dried and impregnated and the space between the coil assembly and container is filled with insulating compound.

The mutual inductance of a typical coil varies as shown in figure 8 as the cores are moved. The range, with the shunts disconnected, is approximately +1.6 to −1.6 microhenries, which is covered in about 16 turns of the screw (a total core travel of 0.5 inch). With the shunts connected, the effective mutual inductance at a given set-

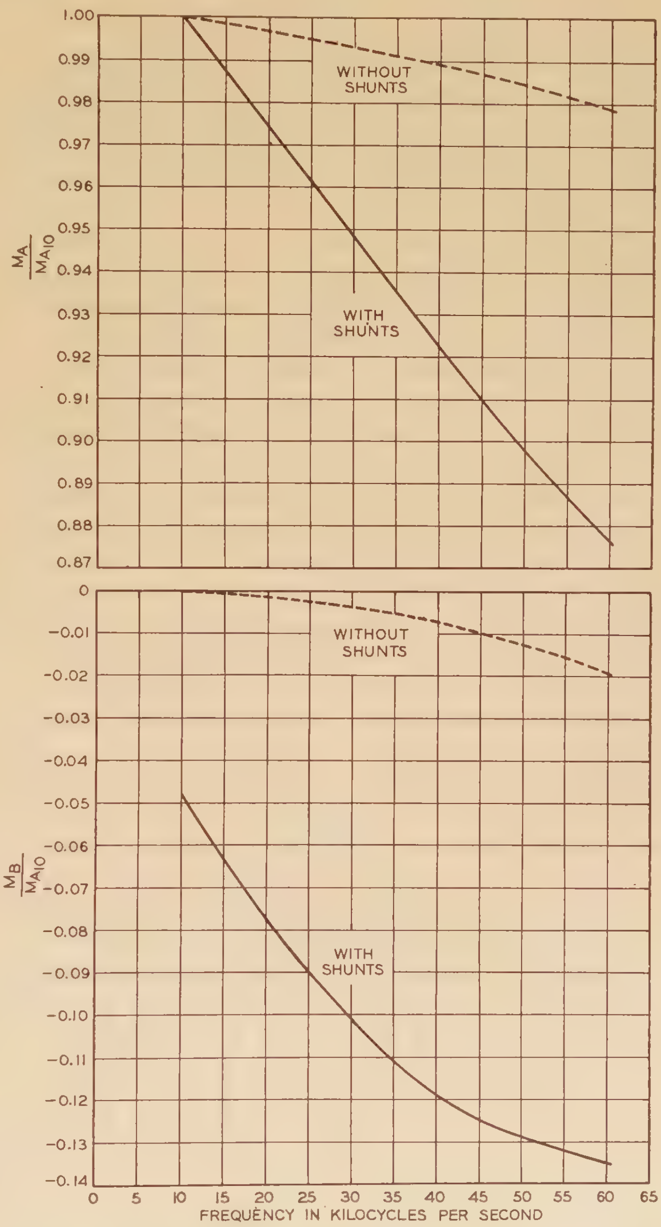


Figure 9. Variation of M_a and M_b components of trial balancing coil with frequency

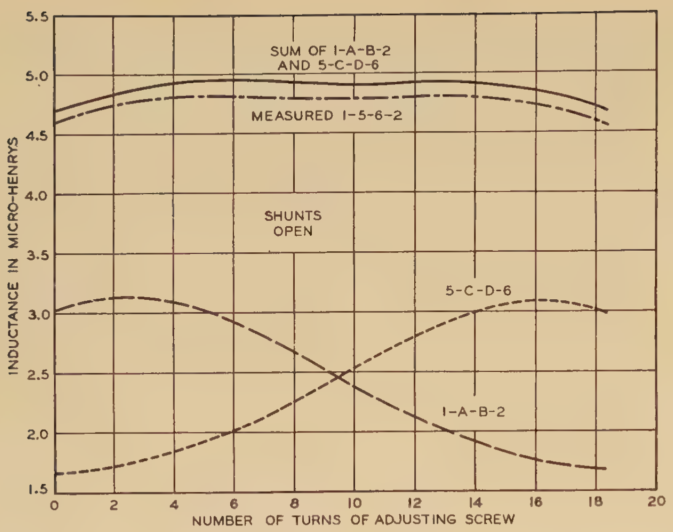


Figure 10. Series inductance of nonshunted trial balancing coil

ting becomes less as the frequency rises, the two components, M_a and M_b, varying with frequency as shown in figure 9. To determine the proper values of L_s and R_s for the shunt, allowance must be made for the complex mutual inductance inherent in the coil due to proximity effect within the windings.

The series inductance of the balancing coil without shunts varies as shown in figure 10. As the cores are moved, the inductances of windings 1-*A*-*B*-2 and 5-*C*-*D*-6 (figure 5) behave as shown by their respective curves, one increasing as the other decreases. The sum of these two curves is shown by the dotted line, and the measured value of 1-5-6-2 is shown by the solid line. It is seen that the over-all self-inductance of 1-5-6-2 is constant to within ±0.1 microhenry. The difference between the curves (about 0.1 microhenry) is caused by the slight mutual inductance existing between winding 1-*A*-*B*-2 and 5-*C*-*D*-6, which is negative owing to reversed winding direction in this side of the balancing coil. The measured inductance around 3-7-8-4 would slightly exceed that obtained by adding the inductances of the two sections owing to positive mutual inductance between the two ends. These end effects could be reduced by greater separation of the two sets of windings, but this refinement is not necessary.

When the shunts are connected, the inductance around 1-5-6-2 is lowered slightly, and the effective resistance is increased. To simplify the capacitance loading and in order not to introduce more resistance in one cable pair than another, the balancing coil assembly is so arranged that shunted and nonshunted windings are alternately introduced into a pair.

BALANCING PANELS

In assembling the balancing coils on panels, the same number of coils should be traversed on each of two pairs before reaching the coil that balances these two pairs, in order that the phase shift up to this balancing coil on one pair will be essentially the same as that on the other pair. If these phase shifts differed materially, the coil setting for minimum crosstalk when one pair is the disturbing circuit might be quite different from the best setting when the other pair is the disturbing circuit. To obtain this equality objective a "criss cross" arrangement, as shown schematically on figure 11, was devised, whereby the number of coils on one pair up to a particular balancing coil never differs by more than one from the number of coils on the other pair up to this same balancing coil.

For economic reasons it is undesirable to install a complete panel for the ultimate number of pairs, possibly 100 in some cases, but rather to install sections conforming more closely to the circuit growth. The placing at different times and properly connecting of sections obtained from the 100-pair criss-cross panel and at the same time maintaining service on operating circuits appeared rather formidable. This problem was solved by the use of two types of criss-cross panels; an intragroup panel for balancing within one group of carrier pairs and an intergroup panel for balancing pairs in one group against pairs in a second group of equal size. In the present design, an intragroup panel takes care of 20 pairs (190 combinations) and an intergroup panel of the 400 combinations between two 20-pair groups. To maintain phase equality through a number of panels, it is necessary to install them following a definite pattern. Figure 12 shows a suitable pattern for the 15 panels required for 100 pairs.

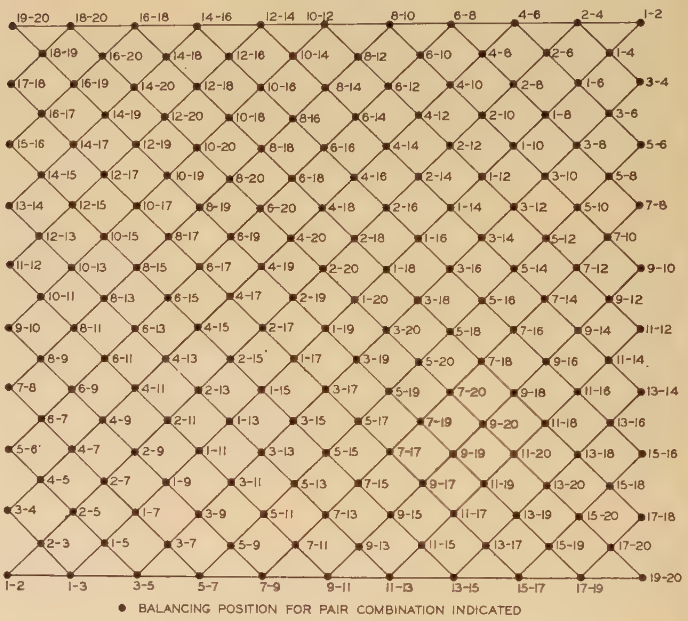


Figure 11. Schematic of criss-cross wiring for 20-pair balancing panel, designed to maintain phase equality of coils

In the criss-cross scheme (figure 11) the side-to-side combinations, which are those marked 1/2, 3/4, 5/6, etc., appear twice, i.e., along the left and right edges of the panel. Advantage of this is taken by installing balancing coils at both locations. This is done because one side-to-side coil of about 1.3 microhenries may not be large enough in all cases in spite of the fact that the mean side-to-side crosstalk has been reduced nine decibels by poling.

Balancing Procedure

As stated above, the far-end crosstalk in a repeater section cannot be balanced out completely over the frequency range with a single balancing unit. To determine the balanceable as distinct from the nonbalanceable crosstalk, involves crosstalk measurements in phase and magnitude at a number of frequencies, using each pair of a two-pair combination as a disturbing circuit in turn. The balanceable crosstalk may then be separated from the nonbalanceable crosstalk by computation. Balancing by this method would be impracticable because of the time required. As a practical scheme, it has been shown that balancing at a frequency of about 40 kilocycles will produce satisfactory results over the type-*K* range even though part of the nonbalanceable crosstalk may be neutralized at this frequency. This is theoretically undesirable since the crosstalk reduction at other frequencies is impaired.

To prevent undue interference into operating carrier circuits when balancing, a frequency falling between the transmitted bands must be used. For this reason, the balancing coils are adjusted at a test frequency of 39.85 kilocycles and a measurement to check the suitability of the adjustment is made at 28.15 kilocycles. Figure 13 shows the crosstalk versus frequency before and after coil balancing by this method on three repeater sections.

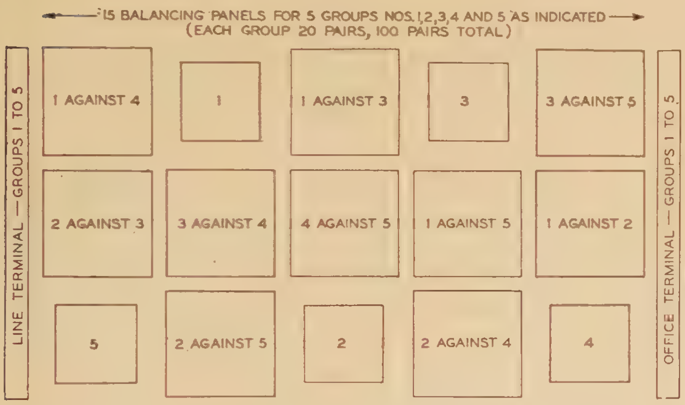

15 BALANCING PANELS FOR 5 GROUPS NOS. 1,2,3,4 AND 5 AS INDICATED
(EACH GROUP 20 PAIRS, 100 PAIRS TOTAL)
LINE TERMINAL — GROUPS 1 TO 5
1 AGAINST 4
1
1 AGAINST 3
3
3 AGAINST 5
2 AGAINST 3
3 AGAINST 4
4 AGAINST 5
1 AGAINST 5
1 AGAINST 2
5
2 AGAINST 5
2
2 AGAINST 4
4
OFFICE TERMINAL — GROUPS 1 TO 5

Figure 12. Allocation of balancing panels designed to maintain phase equalization of coils at all stages. Panels with suitable cross-connections between them are installed in following order

For first group—Install 1
Add second group—Add 2, and 1 against 2
Add third group—Add 3, 1 against 3, and 2 against 3
Etc.

Additional Crosstalk Remedial Measures

Although poling as well as balancing is done to reduce side-to-side crosstalk, this crosstalk is still considerably greater than the pair-to-pair crosstalk. For this reason, side-to-side crosstalk is diluted among the pair-to-pair combinations by a system of quad splitting at repeater points.

The crosstalk after balancing (figure 13) is considerably higher at the upper end of the frequency band than at the lower end. Consequently, if circuits were set up to use the same channel throughout, the crosstalk in the upper-frequency channels would be materially greater than that in the lower-frequency channels. In order that all circuits may be equally satisfactory from the crosstalk standpoint, a system of special channel assignments in successive intervals, say 500 to 1,000 miles, can be used. This will tend to equalize both the crosstalk and the noise on all circuits, thus permitting a somewhat cheaper design than if each channel had to meet the crosstalk and noise limits by itself.

Noise

Besides babble (noted above) many other sources of noise need to be considered in cable carrier design. Figure 14, which shows the approximate magnitude of several of these if no means are taken to suppress them, indicates the noise at the end of a single 17-mile repeater section when amplified by a repeater whose gain equals the hot-weather line loss. Curve *A* shows the unavoidable lower limit of noise, that produced by thermal agitation of the electrons in the cable conductors and the repeater.[2] This amounts to about 2×10^{-17} watts per telephone channel per repeater section, at the repeater input. If there were no other noise sources, the repeater section length would necessarily be limited by this effect. Curve *B* shows the sum of thermal noise and noise due to the vacuum tubes in the repeaters, which is little in excess of thermal noise alone. The other three curves show noises of considerably higher magnitude which require suppression in order to arrive at an economical carrier system. Curve *E* shows the order of magnitude of noise on carrier circuits due to connecting open-wire pairs directly to noncarrier pairs in the outside cable near the carrier repeater input. The source of the noise is heavy atmospheric static of a magnitude experienced several times during the summer. The other curves show typical magnitudes of noise originating in the existing telegraph and voice frequency telephone plant; this is generated in existing repeater stations and transmitted by the noncarrier pairs to the outside cable where it is induced into the carrier pairs. Curve *D* rep-

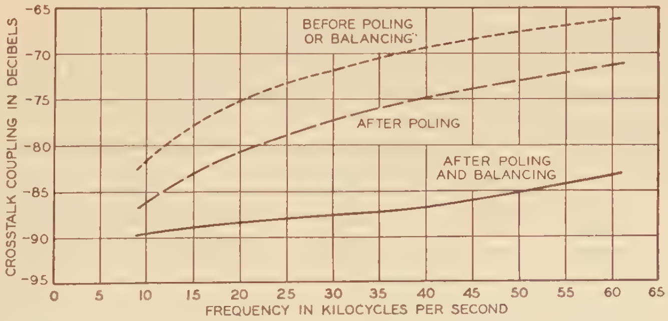


Figure 13. Root-mean-square far-end crosstalk per repeater section from measurements on three repeater sections

resents the situation at a combined telephone and telegraph repeater station, and curve *C*, the situation at a station where there are no telegraph repeaters.

Figure 15 indicates the results after suppression measures have been applied. As shown, at the top frequency, which controls the carrier repeater section length, these sources of noise have been reduced to be well below thermal plus tube noise. It is also shown that the noise due to heavy atmospheric static induced directly into a carrier pair in the outside cable is below thermal plus tube noise at the top frequency.

There are additional types of noise, not shown, whose sources lie within the carrier system: e.g., modulation in amplifiers, intersystem cross-induction, battery noise. While control of such noise is an integral part of the fundamental carrier system design, it is not the purpose of this paper to cover this class of noise.

CONDUCTORS TAPPING THE CARRIER CABLE

Carrier noise may come from open-wire pairs which connect to conductors in the cable. Its sources may be static; corona on power lines; power-line carrier or other carrier-frequency voltages on power lines paralleling the open wire; induction from radiotelegraph stations; or carrier frequency voltages arising in the office to which the open wire is connected, such as voltages generated by d-c telegraph or telephone signaling systems. The limited experience to date indicates that, in a long cable carrier system, the effect of heavy static will be larger than that of the other sources if telephone and power supply plants are co-ordinated so as to be satisfactory from voice frequency and low frequency standpoints. Branch cables connected to the carrier cable have a similar but generally smaller effect than that of open-wire taps.

Figure 16 illustrates the path followed by this induction. A voltage to ground impressed on the open-wire pairs passes by secondary induction over to the carrier pairs in the cable, and, on account of the unbalance to ground of these pairs, produces a metallic voltage on these pairs at the repeater input. The effect may be greatly reduced by interposing a filter at the junction of the open wire and the cable.

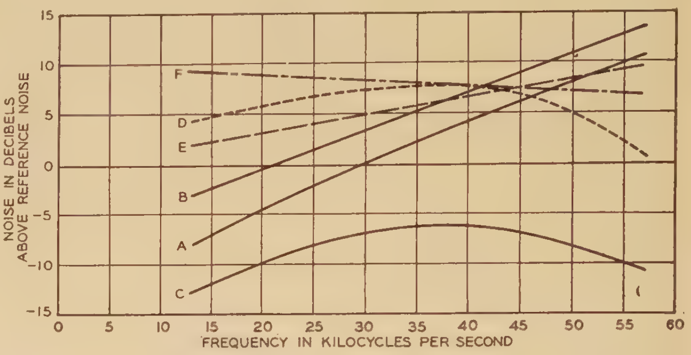


Figure 15. Noise, subsequent to suppression measures, per repeater section at output of repeater whose gain equals line loss

A to *E*—Same sources as in figure 14
F—Noise from heavy static induced directly into outside cable

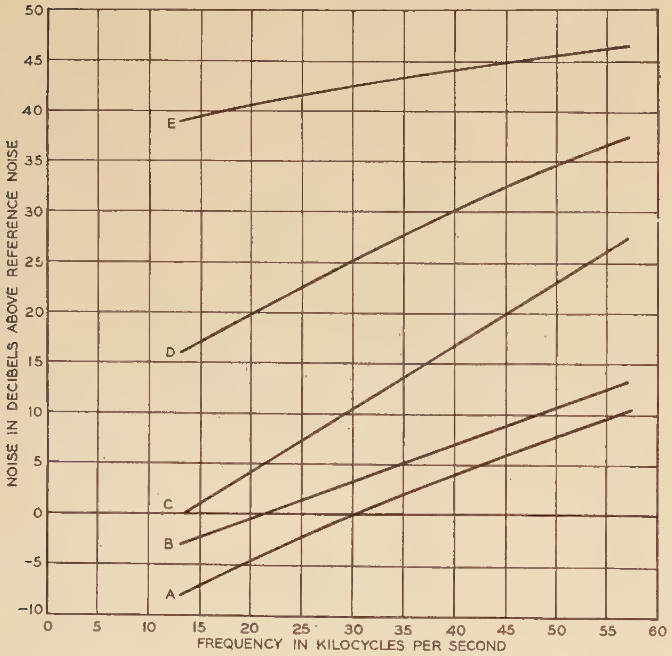


Figure 14. Noise, prior to suppression measures, per repeater section at output of repeater whose gain equals line loss

A—Noise from thermal agitation
B—Thermal agitation plus tube noise
C—Noise from voice frequency telephone repeater office
D—Noise from telephone and telegraph repeater office
E—Noise from heavy static on open-wire tap close to carrier repeater input

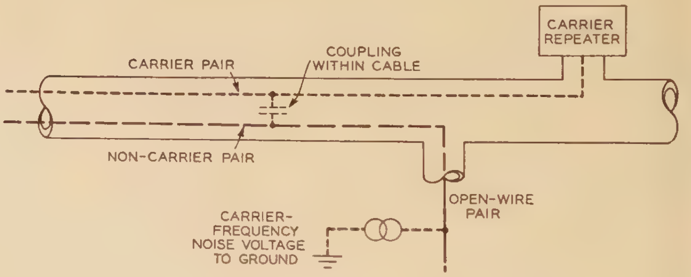


Figure 16. Schematic of path followed by induction from open-wire taps

It is necessary to filter only the longitudinal circuit at an open-wire tap, because; (1) the voltage to ground on the open wire is much larger than the metallic circuit voltage, and (2) the coupling between the longitudinal circuit and the disturbed carrier pair is greater than the coupling between metallic circuits.

Figure 17 is a schematic diagram of the longitudinal filter developed for a phantom group. It consists of two longitudinal retardation coils and a set of condensers connected between the line wires and the cable sheath. This filter has relatively high carrier frequency longitudinal impedance to minimize effects of impedance in the ground connection. The major portion of the carrier frequency impedance of the coils is obtained by designing them to have high core loss at these frequencies. The filter has little effect on voice frequency transmission, precaution having been taken to hold the transmission loss, crosstalk and unbalance to ground to low values.

Noise Arising in Existing Repeater Offices

The noise caused by carrier frequency voltages generated in existing repeater offices is due to d-c telegraph, telephone speech and signaling voltages, power supply, etc. Figure 1 shows the path by which they reach the carrier plant and the means used to suppress them. In this figure, N represents a source of carrier-frequency voltage in a repeater office, connected to a voice frequency pair which transmits this voltage into the outside cable where it is induced on the carrier pairs. These voltages are reduced by inserting suppression coils in the longitudinal voice frequency paths at the junction between the office and the outside cable connected to carrier inputs.

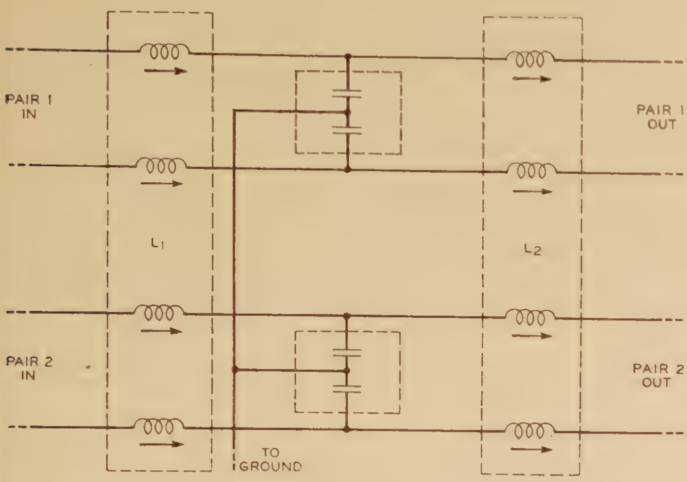


Figure 17. Schematic of longitudinal filter

The design of coils giving the requisite carrier-frequency suppression without appreciably affecting voice-frequency transmission on the circuits in which they are connected was difficult. One coil is used for each phantom group. Each coil has sixteen windings, four for each line wire. These windings are so paired and disposed about the core as to make possible very small side-to-side and phantom-to-side crosstalk between line windings. They also permit obtaining very small leakage flux in both the sides and the phantoms; hence the coils introduce very small transmission loss in their voice-frequency circuits. The leakage impedance of the coils plus the impedance of the cable stub used to connect them into the circuit is held down so that the effect on repeater singing and echoes in the voice circuits is very small. The coils are so wound that their longitudinal inductance is in antiresonance with their distributed longitudinal capacitance at approximately the top cable carrier frequency, resulting in a large increase in their suppression in this critical frequency range. The longitudinal impedance of one of these coils, and the approximate suppression which a set of them provides, are shown in figure 18.

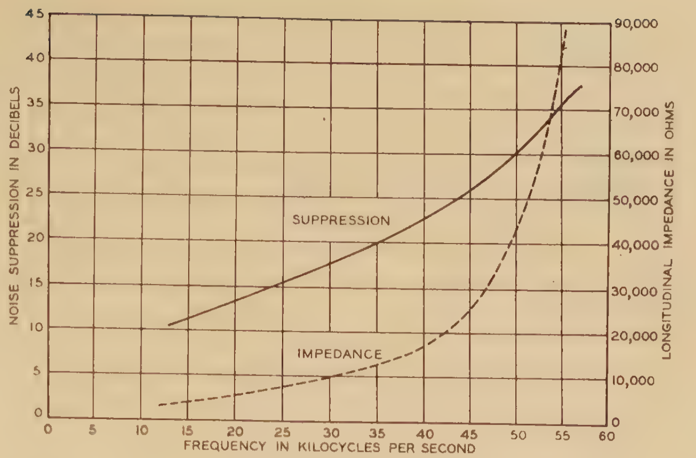


Figure 18. Longitudinal impedance and suppression of noise suppression coils

In addition, the carrier circuits are carefully separated, electrically and physically, from existing voice-frequency circuits in common repeater stations. To this end the carrier pairs in the outside cable are brought out on the line side of the noise suppression coils into a separate cable connected directly to a sealed terminal. From this terminal they are carried in shielded wire to the units in the carrier office and then to a similar sealed terminal leading to the outside cable in the opposite direction. Filters for filament and plate battery supply are included in the carrier amplifiers and additional filament battery supply filters are provided at the carrier fuse panels.

References

1. Cable Crosstalk—Effect of Non-Uniform Current Distribution in the Wires, R. N. Hunter and R. P. Booth. *Bell System Technical Journal*, April 1935.

2. J. B. Johnson, *Phys. Rev.*, 32, 97 (1928); H. Nyquist, *Phys. Rev.*, 32, 110 (1928).

Discussion

A Carrier Telephone System for Toll Cables

C. W. Green and E. I. Green

Cable Carrier-Telephone Terminals

R. W. Chesnut, L. M. Ilgenfritz, and A. Kenner

Crystal Channel Filters for the Cable Carrier System

C. E. Lane

Crosstalk and Noise Features of Cable Carrier-Telephone System

M. A. Weaver, R. S. Tucker, and P. S. Darnell

W. H. Capen (International Telephone and Telegraph Corporation, New York, N. Y.): The authors of this group of papers on carrier-cable developments should be highly complimented on the excellent presentation of this most interesting subject. Not many years ago this type of system would have been impossible of production. However, with the vacuum tube now in its high state of perfection, the latest filter technique, the piezo crystal, the Black feedback amplifier, and a clear understanding of the factors involved and how to control them, this new economical telephone transmission system has been produced.

Working along parallel lines and based upon the early technique carried out by the Bell System and described in a paper by Messrs. Clark and Kendall (item 1 of the bibliography), a 12-channel system has been developed by a subsidiary of the International Telephone and Telegraph Corporation, and first installed for the British Post Office between Bristol and Plymouth, a distance of approximately 123 miles.

In the bibliography attached to the paper by Messrs. C. W. and E. I. Green, reference is made to a paper by Messrs. Angwin and Mack, published in the *Journal* of the IEE, and entitled, "Modern Systems of Multi-Channel Telephony on Cables." This paper includes a description of the English 12-channel system. As there are some differences between the British system and that described in the papers under discussion, a brief review of the Bristol-Plymouth system may be of interest. The system makes use of a frequency band extending from approximately 12 to 60 kilocycles with a carrier spacing of four kilocycles. Only the lower sideband is transmitted.

Separate cables are used for the "go" and "return" circuits and these were designed and installed especially for the application of the 12-channel system. Each cable is a paired cable; i.e., pairs were not twisted together in groups of two to form quads as is usual in voice-frequency cables. The chief advantages of this feature are that the higher couplings between pairs within a quad are avoided and that the effective resistance at 60 kilocycles for a given capacitance is less than in a quadded cable. However, future cables will probably be mainly of the star quad type because of the better space factor. Each cable comprises 19 40-pound pairs, which was the maximum number that would permit of the two cables (with special protection) being drawn into the normal three-inch duct lines. The outside diameter of each cable is 1.1 inches. Each pair was made with a different length of twist to minimize mutual impedance between pairs. To minimize increased resistance due to eddy currents induced in the sheath by pairs near the sheath, the lead sheath was spaced from the outer layer by a thick layer of insulation.

At 60 kilocycles the contribution of skin and proximity effects to the effective resistance of pairs in telephone cables tends to become the dominating factor when the wires are increased in diameter, and it was found that little advantage would be gained by increasing the gauge beyond 40 pounds per mile, which was decided upon. The maximum spacing of repeaters was fixed at 22 miles, with an average of 18 miles, corresponding to an attenuation of somewhat less than 60 decibels per repeater section.

In addition to the special design of the cable, it was, of course, necessary to balance the various pairs against each other in order to reduce crosstalk. It was found, however, that sufficient reduction could be obtained by the use of condensers alone. These were installed at the midpoint of each repeater section. By means of these condensers the average far end crosstalk was reduced from about 72.5 decibels to 85.5 decibels, while the maximum crosstalk was reduced from 63 decibels to 75 decibels.

The filters are of conventional design electrically, consisting of inductance coils and condensers. In view of the higher frequencies involved, the filter sections must be made more accurately than formerly, and so each arm of a filter comprising a coil and condenser in series (or in shunt) has been made into a unit and resonated to a predetermined frequency by means of a small variable condenser, before being assembled on the filter mounting plate. In this way the accuracy of the filters has been improved so that the characteristics of the highest channels are similar to those formerly obtained at frequencies not higher than 30 kilocycles.

The amplifiers follow closely the principles described by H. S. Black of the Bell Telephone Laboratories. A three-stage feedback amplifier is used, the feedback circuit being connected between the output of the last stage and the input of the first stage. A maximum overall gain of 65 decibels can be obtained.

The over-all line characteristics taken at carrier frequencies on the whole repeatered circuit from Bristol to Plymouth showed a total variation, down to a frequency of 20 kilocycles of less than one decibel. The total variation of output level at any repeater station was found not to exceed two decibels over the range required for the 12 channels, and the over-all equalization was such that the effect on the frequency characteristic of any one channel was almost negligible.

In order to make some estimate of the effect of connecting systems in tandem, arrangements were made on one of the Bristol-Plymouth systems to loop back the channels on the two-wire sides. Using three channels in tandem, the quality as judged by ear was no different from that obtained on the normal circuit between Bristol and Plymouth. With six channels in series, the quality was still good but some slight deterioration could be detected. As a final test the whole 12 channels were looped back on one another, when it was found that, if the gains were suitably adjusted so as to give an over-all equivalent of three decibels, the speech, although considerably degraded, was still easily understandable. This last case is equivalent to a circuit approximately 1,500 miles in length, in which the signals pass through 96 repeaters in tandem.

The degradation referred to was, of course, due chiefly to the accumulation of terminal distortion and would not be present on circuits of the same total length with carrier modulating equipment provided only at its ends.

Equipment for six 12-channel systems was installed initially, three of the systems operating between Bristol and Exeter and three between Bristol and Plymouth; 31 circuits were placed in service during December 1936. The number of circuits has since been increased and several of these circuits are extended, four wire, on audio circuits to London.

The results obtained on the Bristol-Plymouth installation have justified the expectations with which the experiment was launched, and in the planning of the trunk network of Great Britain 12-channel carrier has already taken its place as the premier means of providing additional long circuits.

Plans are now actively under way for installing this type of carrier system on nearly all of the main routes from Plymouth in the south, to Aberdeen and Inverness in North Scotland. A total of nearly 17,000 two-way channel miles of this type of system are now in operation. Several thousand additional two-way channel miles are being installed, and further systems ordered.

Glen Ireland (American Telephone and Telegraph Company, New York, N. Y.): We are greatly indebted to the authors of this group of papers for this story about the development of the cable-carrier system.

The first commercial installation of the cable-carrier system in this country will be placed in permanent service between Detroit, Mich., and South Bend, Ind., a distance of about 200 miles, by the spring of this year. Other projects will follow and by the end of this year, cable carrier probably will have been applied along 830 miles of toll-cable route. Along about 560 miles of the route, the cable carrier will utilize conductors in two existing cables of the type previously placed for voice-frequency use. For the remaining part of the distance where only one such existing cable is available, a small paralleling cable of a special design is being provided. In connection with the engineering of these routes, it has been necessary to select the pairs most suitable for unloading and carrier usage, to survey the cables throughout to make sure that they were suitable in all respects and that necessary noise filters were provided for the open-wire and cable taps. Sites for 34 auxiliary repeater stations have been selected and suitable buildings of the type described in the Green and Green paper either have been or soon will be constructed. To the extent practicable, standardized equipment layouts are being provided in both the main and auxiliary repeater stations.

Cable carrier systems in the future are expected to find their principal field of use along the present long toll cable routes, where conductors in existing cables may be utilized and where there will be a demand for large numbers of additional circuits over 80–100 miles in length. A survey of the present toll cable network indicates that there are some 2,900 miles of route having at least two cables and 6,500 miles of single-cable route that might be considered as potential candidates for the application of some form of cable carrier. Among the more important routes having at least two existing cables are New York-Chicago, Boston-Washington, New York-Buffalo, and Pittsburg-Terre Haute, Ind. The application of cable carrier to the existing toll cable network will be greatly aided by the fact that through previous standardization toll cable of known characteristics and quality and of a given gauge is available throughout the network. This is particularly important in connection with the crosstalk balancing work and the equalization of the high-frequency line.

The general introduction of cable carrier should result in marked improvement in the telephone toll service. Its availability, together with that of other broad-band carrier systems, has been one of the principal factors which makes it practicable for the Bell System to consider the introduction of improved transmission standards for the longer toll circuits. The greater velocity of transmission provided by the nonloaded cable conductors and the resulting reduction in delay effects are important factors in making this possible. The wider band of frequencies which are effectively transmitted by the cable carrier is also an important factor in improving transmission, this latter factor contributing materially to the naturalness and ease of conversation. The cable carrier systems also are expected to be very quiet. This is due in part to careful design and in part to the relative freedom of the high-frequency cable carrier circuits from the interfering effects of neighboring power systems.

Some of the maintenance arrangements mentioned in the paper are of considerable interest to the operating people. In particular the arrangement where amplifiers or a spare circuit link may be quickly substituted with little or no interruption of service is expected to be of considerable value to the field maintenance forces.

E. I. Green (for all authors): The authors have noted with interest the comments on the papers, particularly the discussion by Mr. Capen of the application of cable carrier between Bristol and Plymouth and elsewhere in Great Britain. As Mr. Capen has indicated, the British system follows to a considerable extent along the lines of the experimental system installed at Morristown, N. J., as described to the Institute in 1933, and differs in a number of respects from the present type-*K* system. The British system is applied to new cable installed underground. This cable is of special design and is nonquadded with 16-gauge conductors. The type-*K* system, on the other hand, is applied to existing cables installed either aerially or underground, and employs ordinary 19-gauge quadded conductors. The use of existing toll cables for the type-*K* system greatly augmented the problems of crosstalk and transmission regulation which had to be solved.

Harmonic-Current-Restrained Relays for Differential Protection

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DIFFERENTIAL relaying is the commonly accepted means of protecting large power transformers, a-c generators, and station bus systems against internal faults.[1] The methods and circuits employed in various instances, while differing in detail, are all fundamentally the same in basic principle. Briefly speaking, this principle consists in continuously comparing in each phase the current entering the protected equipment with that leaving. As illustrated in the generalized single-line diagram figure 1, the comparison is made by means of current transformers of suitable ratios placed in all the power circuits connecting with the protected equipment. If current transformation takes place within the equipment as in the case of a power transformer, the ratios of the current transformers placed in the various circuits are chosen to have relative values corresponding to the transformation ratios so that the current transformer secondary currents may be compared on a 1:1 basis. The secondary windings of all the current transformers in each phase are connected in parallel with each other to a special kind of current relay usually called a "differential" relay. The current transformers are all connected in the same polarity with respect to the direction of the protected zone so that currents entering and leaving the protected zone will be represented in the secondary circuit by currents of opposite polarities. Normally, with sound equipment these positive and negative components will be equal, except for negligible exciting currents, and their algebraic sum which by the connection is applied to the relay coil will be essentially zero. When a fault occurs within the protected zone, however, the balance is upset and a difference current proportional to the fault current flows in the coil of the relay, causing it to operate and trip circuit breakers in all the connecting circuits, removing the faulted equipment from service.

It is important that the faulted equipment be isolated as quickly as possible after the fault occurs, not only to limit damage to the equipment but also to minimize the length of time that the voltage is depressed. A prolonged period of low voltage is likely to result in loss of synchronism between rotating machines. When this occurs the excessive current drawn by the machines out of step often causes other protective relays to operate, tripping out circuit breakers until the power system is split apart and a major interruption of service results. A prolonged period of low voltage also results in loss of important loads due to operation of undervoltage devices. It is just as important that loaded equipment should not be needlessly cut out of service due to false operation of the relays when no internal fault is present. Unbalanced currents may sometimes flow in differential relay circuits when no internal fault is present due to causes which will be discussed below. These will cause false operation of the differential relay unless means are used to prevent it. The means hitherto employed and their shortcomings will be discussed, and a new method, free of these shortcomings, and suitable for general application will be described.

Causes of False Differential Currents

A. Departure of Current Transformer Ratios From Their Normal Values

When heavy current, due perhaps to an external fault, is drawn through the equipment protected by differential relaying, the current transformers become saturated and their ratios depart from their normal values by an amount depending on their designs, the amounts and power factors of their secondary burdens and the magnitude of the fault current. With full rated burden connected to the current transformer secondary and with currents of 20 times normal load value passing through the primary the ratio change may be so serious that only half the current calculated from the normal ratio flows in the secondary circuit. With lighter secondary burdens or lower values of primary current the departure is less severe but still considerable. In the special case where only two current transformers are involved, if the characteristics are matched, the secondary current sum will still be zero and no difference current will flow in the relay. With more than two current transformers, however, differences in the current-transformer characteristics or unequal distribution of the primary currents between the several current transformers will cause a difference current to appear which tends to operate the relay.

The usual method of preventing relay operation on differential currents due to current transformer saturation has been to use what is known as a "percentage differential relay." This type of relay compares the differential current with the through current and requires that the differential current exceed a certain percentage of the through current before the relay operates. This is accomplished by connecting a restraining coil in the relay in series with each of the current transformer secondaries. This type relay has been widely and successfully used on a-c generators and on two- and three-winding transformers.[2] Where only two circuits are involved, as in the case of the generator and the two winding transformer, the relative directions of the currents in the two current

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L. F. Kennedy is employed in the relay engineering section of the General Electric Company, Philadelphia, Pa., and C. D. Hayward is development engineer for the same company.

[1] For all numbered references, see list at end of paper.

transformer secondaries is always the same when the equipment is sound, so both restraining coils may be placed on a single restraint magnet acting on the armature. In the general three-winding transformer where the relative direction of current flow in the three windings may be different under different conditions, it is necessary that the three restraint coils be placed on three separate magnets acting on the armature separately. Where more than three windings are involved or similarly in the case of bus systems where there are many circuits, it has not been found practical to use this type of relay because of the complications involved in building a relay with so many restraint magnets.

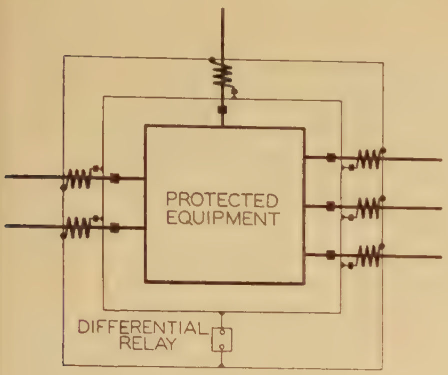


Figure 1. Fundamental circuit for differential relay protection

B. Magnetizing Inrush Current in Power Transformers

It is a well-known fact that when a switch is closed, suddenly applying potential to a winding of a previously de-energized transformer, the transient magnetizing current which flows may for a time reach very high values depending upon the amount of residual magnetization left in the transformer core from former operation and upon the point of the voltage wave at which the switch is closed.[3] In comparison with normal steady-state magnetizing current which for large power transformers is in the neighborhood of one per cent of full-load current, this transient magnetizing inrush current often reaches values of eight to ten times full load current (800 to 1,000 times normal magnetizing current). This magnetizing current flows in the transformer primary winding only and hence causes a corresponding difference current to flow in the differential relay.

The tendency of differential relays to operate on magnetizing inrush currents in power transformers has been resisted in the past either by using a slow acting relay, or by desensitizing the relay (or rendering it altogether inoperative) during a definite time following the application of potential, thus enabling it to ride over the magnetizing inrush period. This latter means has been accomplished by the use of a time-delay voltage operated auxiliary relay energized from a potential transformer connected across the power transformer winding and having contacts connected to remove a shunt around the operating coil (or to close a trip circuit contact in series with the differential relay contacts). Both these methods are unsatisfactory when judged by the standards of modern protective relay practice, the first because of its slowness on internal faults and the second because of the length of time that reduced protection is given the equipment. Cases are often encountered, particularly in large 25-cycle transformer installations where the inrush transient period may last for several seconds. Considerable damage can be done both to the transformer and to the system stability if a fault already present in the transformer when potential is applied is allowed to remain on for this length of time. Another objection lies in the failure of this method to prevent operation of the differential relay in cases occasionally encountered where magnetizing inrush currents appear when the transformer voltage, after being momentarily depressed by a close external fault, suddenly rises again as the fault is cleared.

C. Magnetizing Inrush Current in Current Transformers

Magnetizing inrush currents of considerable magnitude may also appear in current transformers. Heavy currents suddenly drawn through current transformers previously carrying little or no current cause magnetizing inrush currents to flow in much the same way as the sudden application of potential does in the case of power transformers. The magnitude of the inrush current depends upon the design of the current transformer, the magnitude of the fault current and the amount of secondary burden as well as the point of the wave at which the heavy current begins to flow and the amount of flux present in the core at that time. This inrush current flows in the primary of the current transformer only. The secondary current appears as a transformation of the primary current with the inrush current subtracted. In the differential relay connection the several current transformers will in general draw varying amounts of inrush current on through faults so that a difference current due to this cause will often flow in the relay.

Figure 2. Differential current due to an internal fault

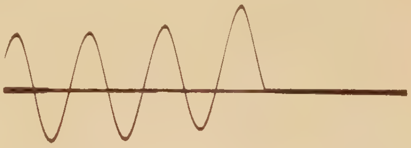
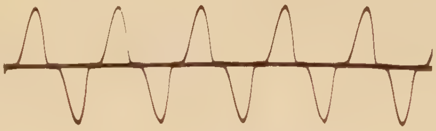


Figure 3. Differential current due to saturation of current transformers on heavy through fault current



Where the percentage differential relay may be used, as in the case of a-c generators and two- or three-winding transformers, the chance of having false relay operation due to current transformer magnetizing inrush currents is reduced by the use of a liberal percentage of through current restraint. This is not altogether satisfactory, however, since it reduces the sensitivity of the relay to internal faults. In applications where the use of a percentage differential relay is impractical, as in the case of many winding transformers or busses involving many circuits, the only recourse has been to the use of relays set for high pick-up current or to operate slowly enough to ride over the inrush period. This system of course leaves much to be desired.

Harmonic Current Restraint

A new method of preventing the false operation of differential relays on unbalanced currents due to any or all the causes described above has recently been applied. We have called it the principle of harmonic current restraint. It takes advantage of the difference in wave form between the differential current caused by a true internal fault and that caused by current transformer saturation or magnetizing inrush currents to restrain the relay from operating except when a fault exists within the protected zone. Oscillograms illustrating typical wave forms of these various currents are shown in figures 2, 3, and 4.

It is convenient when working with non-sine current waves of this kind to consider them as being composed of an infinite series of sine wave components of ascending order of frequencies according to the Fourier expansion:

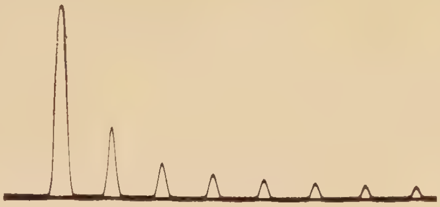


Figure 4. Differential current due to magnetizing inrush to either power or current transformer

$$I(t) = I_0 + I_1 \sin(\theta_1 + wt) + I_2 \sin(\theta_2 + 2wt) + I_3 \sin(\theta_3 + 3wt) + \ldots.$$

where

$I(t)$ = the given non-sine wave current, varying as a function of time.

I_0 = the constant or direct-current component.

$I_1, I_2, I_3, \ldots.$ = the maximum values of the fundamental, second harmonic, third harmonic, etc., sine-wave current components.

$\theta_1, \theta_2, \theta_3, \ldots.$ = the phase angle position of the various component waves at the time $t = 0$.

w = $2\pi f$.

f = frequency of fundamental in cycles per second. For the waves we are considering this will be the power line frequency.

A number of methods for evaluating the magnitude coefficients I_0, I_1, I_2, I_3, . ., etc., as well as the angle coefficients θ_1, θ_2, θ_3, . ., are available. Some of these employ graphical means,[4] others mechanical.[5]

Values of the magnitude coefficients computed for the first cycle of each of the waves shown in figures 2, 3, and 4 are given in table I. These are expressed in per cent of the magnitude of the fundamental frequency component. For comparison the crest value of each of the waves in per cent of the crest value of its fundamental component is also given.

While it is understood, of course, that these percentages will vary when the conditions under which the currents appear vary, still for the purpose of our present discussion they may be regarded as typical. The wave due to an internal fault is shown having a rather large displacement, due to the point of the wave at which the fault was initiated. With a symmetrical wave the analysis would show 100 per cent fundamental with zero direct current and negligible harmonic current components.

It will be observed that the waves of the currents which cause undesired operation of the differential relay, that is, currents due to current transformer saturation and magnetizing inrush, differ from the wave of the internal fault current for which relay operation is desired in that they contain considerably greater harmonic components. In a practical relay it is possible to prevent the undesired operations by using these harmonic current components for restraint. The various components may be segregated by means of suitable tuned filter circuits. It is preferable to use all the harmonics for restraint, rather than to select any one alone, for a number of reasons. First of all, it will be observed from Table I that in the two different types of waves for which restraint is desired, different harmonics predominate. Hence, a relay designed to restrain on the second harmonic component only, for example, while suitable for magnetizing inrush currents, would not be properly restrained on currents obtained from saturated current transformers. On the other hand, if the relay were made to restrain on third harmonic only, proper restraint would be obtained on saturated current transformer currents but not on magnetizing inrush. The use of the d-c component alone would not be satisfactory because this component is absent in the saturated current transformer current and also because this component may be lost even on magnetizing inrush waves due to cancellation between phases when the current transformers in a wye-delta power transformer are connected delta-wye, as is the usual practice. Fur-

Table I. Harmonic Wave Analyses of Typical Currents Appearing in Differential Relay Circuits Due to Various Causes

Wave Component		Differential Current Due to: Internal Fault Figure 2	Saturated C. T.'s Figure 3	Magnetizing Inrush Figure 4
I_1	Fundamental	100 per cent	100 per cent	100 per cent
I_0	Direct current	38 per cent	0 per cent	58 per cent
I_2	Second harmonic	9 per cent*	4 per cent	63 per cent
I_3	Third harmonic	4 per cent*	32 per cent	22 per cent
I_4	Fourth harmonic	7 per cent*	9 per cent	5 per cent
I_5	Fifth harmonic	4 per cent*	2 per cent	34 per cent
I_6	Sixth harmonic	6 per cent*	1 per cent	4 per cent
I_7	Seventh harmonic	2 per cent*	3 per cent	3 per cent
	Wave Crest	145 per cent	126 per cent	244 per cent

* NOTE: It may seem surprising to those used to thinking of an offset fault current wave like figure 2 as being composed only of fundamental frequency plus an exponentially decaying direct current to see small quantities of the harmonics listed. This is because the d-c component is assumed by the analysis to have a constant value. The harmonics represent the exponential variation of the d-c component from the beginning to the end of the cycle. Expressing the analysis in this manner is proper because it is the way that the wave appears to the tuned filter circuits of the relay.

thermore, the use of the d-c component alone would result in a relay slow to operate on internal faults where the current wave is appreciably offset.

Practical Application—A Bus Differential Relay

A practical relay with harmonic current restraint, intended primarily for bus differential service is shown in figure 5. The operating characteristics of this relay are as follows:

Pick-up = 5 amperes on sine-wave 60-cycle current.

Operating time ≐ one cycle average (60-cycle base) at twice pick-up or higher.

Burden = 1 volt-ampere at 5 amperes.

This relay was designed with the relatively high 5-ampere pick-up in order to avoid operation of the relay on normal load current in case one of the current transformers in the differential connection should inadvertently have its secondary open circuited. Bus faults invariably draw high enough currents to make extreme sensitivity unnecessary. The internal circuit is shown in figure 6. In this circuit the differential current supplied to the relay is first stepped down by means of a small internal current transformer to a value readily accommodated by standard ratings of the capacitors and rectifier used in the relay.

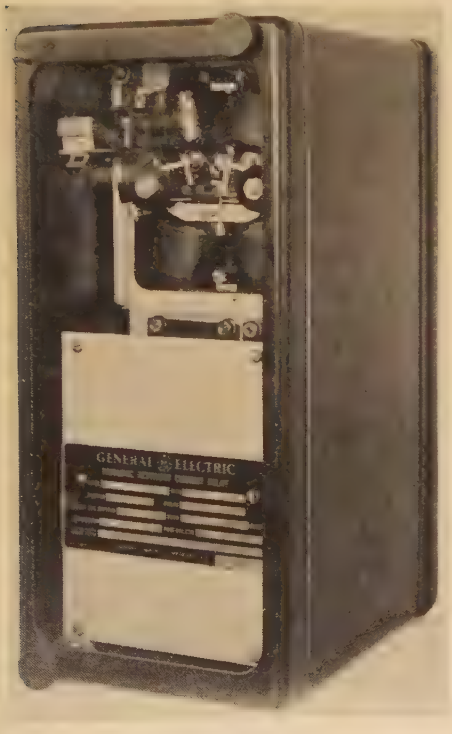


Figure 5. Bus differential relay with harmonic current restraint

Across the secondary of this transformer two parallel circuits are connected, one including the operating coil of the relay and the other the restraining coil. The operating coil circuit branch contains a wave trap made up of a capacitor C_1 and a reactor L_1 in parallel. This trap is tuned to block the predominant harmonic frequency, while the over-all circuit including this trap, the operating coil of the relay and the reactor L_3, is tuned by the capacitor C_3 to have minimum impedance to fundamental frequency. The restraining coil circuit branch has a similar wave trap made up of capacitor C_2 and reactor L_2 in parallel which is tuned to block fundamental frequency. The over-all circuit is untuned. The operating coil circuit branch therefore readily passes current of the fundamental frequency but blocks currents of the predominant and to a large extent the other harmonic frequencies. The restraining-coil circuit branch passes the harmonic frequencies with moderate impedance but blocks the fundamental. Sustained direct current is prevented from flowing in the relay coil circuits by the relay current transformer. Transient current surges may flow in the secondary circuits, however, due to the sudden application of the d-c component when the differential current starts. These current surges have comparatively steep wave fronts and hence pass through capacitors with little impedance. These surges divide between the operating and restraining coil circuit branches essentially in inverse proportion to the relative inductance of the two branches with all capacitors considered as being short circuited. Tests demonstrated that the addition of the reactor L_3 in the operating coil circuit prevents momentary operation of the relay due to these surges on magnetizing inrush currents. The restraint current, having an alternating wave of different frequency from that of the operating current, would, if unrectified, pass through zero at different times than the operating current. At these times the restraining pull would be released and the relay armature would tend to move by momentary flicks in the operating direction. Tests showed these flicks were often of sufficient magnitude to cause contact operation. The use of the rectifier aided by the inductance of the restraint coils was found to be effective in smoothing the restraint current and hence the restraint pull sufficiently to correct this trouble.

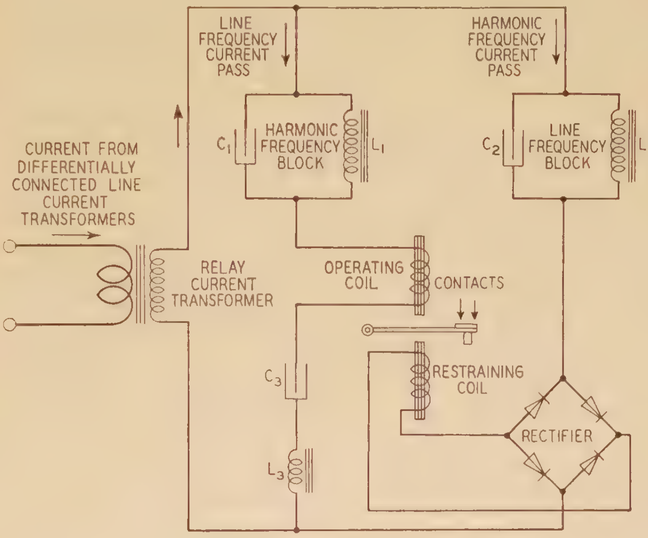

LINE FREQUENCY CURRENT PASS
HARMONIC FREQUENCY CURRENT PASS
C1
HARMONIC FREQUENCY BLOCK
L1
C2
LINE FREQUENCY BLOCK
L2
CURRENT FROM DIFFERENTIALLY CONNECTED LINE CURRENT TRANSFORMERS
RELAY CURRENT TRANSFORMER
OPERATING COIL
CONTACTS
C3
RESTRAINING COIL
RECTIFIER
L3

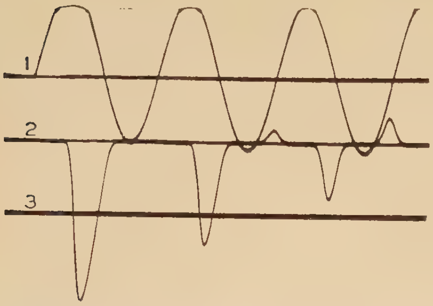
Figure 6. Circuit of differential relay with harmonic current restraint

A differential current due to an internal fault, like figure 2, flows principally in the operating coil and hence causes high speed operation of the relay. A differential current produced by current transformer saturation, like figure 3, or by magnetizing inrush, like figure 4, on the other hand will flow partly in the operating coil and partly in the restraining coil. The restraint magnet air gap is shorter than that of the operating magnet so that the restraint pull predominates and the relay does not operate.

Tests

The relay shown in figure 5 has been thoroughly tested with successful results, under conditions closely simulating those found in actual bus differential relay installations. Two typical oscillograms are shown in figures 7 and 8.

The oscillogram in figure 7 was obtained on a setup representing a through fault. A current of 10,000 amperes root-mean-square was carried into a bus through two lines in parallel and out through a single line. Bushing-type current transformers of 600/5-ampere ratio, one in each of the three lines, were differentially connected to the harmonic current restrained relay. A resistance of three ohms was placed in series with the secondary of the current transformer in the single outgoing line. No burden other than that imposed by the relay and short connecting leads was placed on the other two current transformers. Trace number 1 on the oscillogram is the fault current derived from a shunt, trace number 2 the differential current flowing through the relay, and trace number 3 is of the current in the relay contact circuit. Even though the crest value of the first current loop shown on trace number 2 is 116 amperes, no relay operation occurred.



Trace number 1—Fault current; 10,000 amperes root-mean-square

Trace number 2—Differential relay current. Crest value of first peak = 116 amperes.

Trace number 3—Relay contacts

Figure 7. Test of harmonic current restrained bus differential relay on through fault

Trace number 1—Fault current; 7,200 amperes root-mean-square

Trace number 2—Differential relay current; 59.5 amperes root-mean-square

Trace number 3—Relay contacts

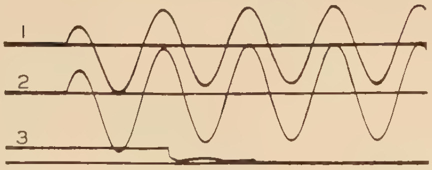


Figure 8. Test of harmonic current restrained bus differential relay on internal fault

The oscillogram in figure 8 was obtained on a set up representing an internal fault on the bus. This setup was similar to the one described above except that the outgoing current flowed through a line connected directly to the bus instead of passing through the third current transformer. The fault current as shown by trace number 1 was 7,200 amperes root-mean-square, the differential current as shown by trace number 2 was 59.5 amperes root-mean-square, while trace number 3 indicates that the relay operated and closed its contacts in approximately one cycle.

Conclusions

1. Differential relaying systems as used for the protection of large power transformers, a-c generators, and station bus systems are subject to false operation on differential currents due to causes other than internal faults in the protected equipment.

2. The means hitherto available to prevent false operation, while satisfactory in some cases, are either impractical or give reduced protection in others.

3. The use of the harmonic components of these currents for restraint is an effective and generally applicable means of preventing false operation while allowing complete, continuous and high-speed protection against internal faults.

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3. Transformer Current and Power Inrushes Under Load, E. B. Kurtz. Electrical Engineering, volume 56, August 1937, page 989.

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Discussion

J. H. Neher (Philadelphia Electric Company, Philadelphia, Pa.): I have had the privilege of watching this relay grow from just a good idea into its present form, and I wish to congradulate Messrs. Kennedy and Hayward on their development of this device and the excellent paper describing it.

The Philadelphia Electric Company was recently faced with the problem of obtaining a differential relay for the protection of the 220-kv bus sections at Plymouth Meeting having an operating time comparable with that of the high-speed relays employed on the lines, which was required by stability considerations, and which at the same time would be immune to operation by transient currents which might appear in the differential circuit on through faults. While high-speed overcurrent relays might have been employed with a sufficiently high setting to override these transients, there is no practical method of determining the maximum value which these transients may assume. It would seem, therefore, that the proper solution of the problem is not to try to guess the value of the transient, but to so arrange the system that the transient, if it appears, will act in such a way that the relay margin is increased rather than diminished thereby. The importance of correct operation of bus differential relays is usually such that the additional complication is well justified.

As a result of this reasoning, we have, or will have shortly, all of our 220- and 66-kv bus sections protected by means of the relay described. These installations are so recent, however, that no operating experience has been obtained to date.

Since both our 220- and 66-kv systems are solidly grounded, the pickup value of the relay could be sufficiently high to make additional restraint against inequality of current transformer ratios unnecessary. If the relay is required to respond to single-phase-to-ground faults on systems where such fault currents may be limited, then a more sensitive relay will be required and its response to the differential currents produced by inequality of current transformer ratios on heavy through faults must be considered. While this type of relay can be constructed with percentage restraint in the usual sense, and the equivalent effect of as many restraining coils as are necessary can be readily provided, nevertheless this complication may not be necessary. The point is that when the secondary currents delivered by the current transformers reach such proportions that the differential current produced by their inequality may equal the normal pickup value of the relay, then these secondary currents may be so rich in harmonics that the effective pickup of the relay may be raised considerably above its normal value, and in effect, percentage restraint is automatically provided. I hope that the authors can give us further information on this point.

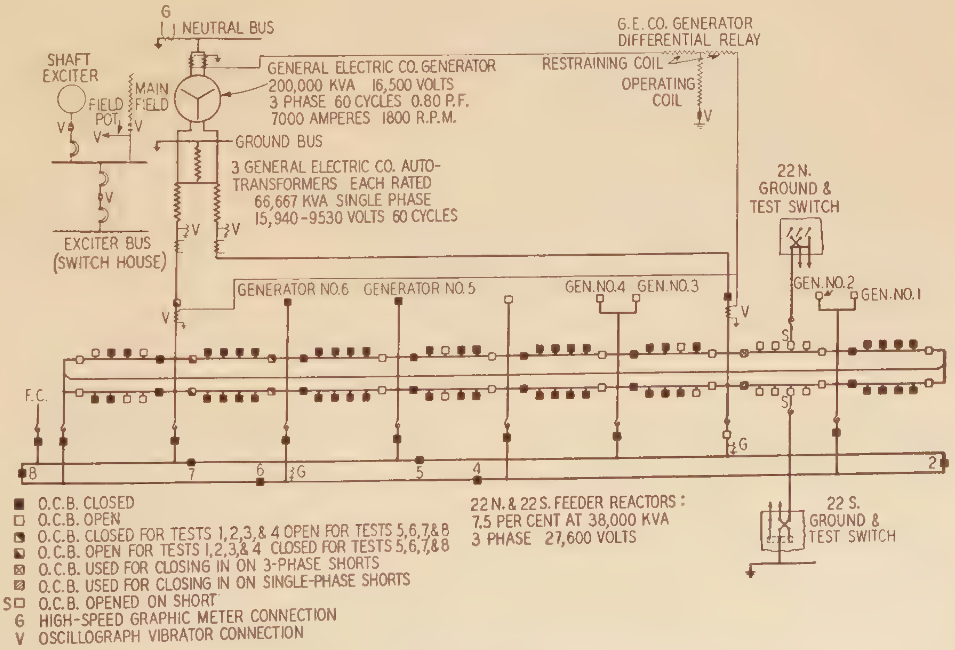
There is a unique feature of the relay which the authors have not mentioned and which may be of interest. In a number of differential relay installations, provision has been made for checking the state of balance of the differential system by an arrangement whereby the operator can insert a low range ammeter in series with the differential relays. In the case of the harmonic-restrained relay described, this same result can be achieved by an arrangement whereby the operator can connect a high resistance rectifier type voltmeter across the secondary of the current transformers contained within the relay. This arrangement is more desirable because the a-c connections to the relay are not disturbed.

R. M. Smith (Westinghouse Electric and Manufacturing Company, Newark, N. J.): This paper should be of unusual interest to relay engineers as it proposes one novel solution for the problem of high-speed protection of electrical equipment.

It is interesting to note that with the exception of the magnetizing inrush of power transformers, the problem of high-speed differential protection is made difficult only because of unfaithful response during faults of the current transformers connected to the protective relay. With proper attention paid to the factors affecting current transformer performance, many simple high-speed relays are available for differential protection, such as the percentage differential relay or even the ever-faithful overcurrent relay. Unfortunately most of the applications for existing equipment finds current transformers ill equipped to handle their burden during maximum through short-circuit conditions without one or more departing severely from true ratio.

The relay described in the paper is apparently adapted for bus differential protection only. The only problem here is saturation of one or more of the current transformers, thus producing current in the differential circuit on a through fault. As shown in figure 3 of the paper this current may be distorted and the relay apparently distinguishes between an internal and external fault by the ratio of the harmonic current to the fundamental. We fail to see why an internal fault will produce a differential current free from harmonics if one or more of the current transformers is saturated. It would appear that there must be some definite ratio in the design of the relay between the amount of fundamental frequency component tending to operate the relay and the harmonic currents tending to restrain the relay, which will produce a balance. In table I the analysis shows that for the differential current due to saturated current transformers there is 32 per cent third harmonic for 100 per cent fundamental for the particular case under consideration. We presume that much less than 32 per cent of harmonics will adequately restrain the relay from operating under this condition so that some safety factor will be provided. The question arises in case of an arcing fault on a bus, when the relay should trip, what per cent of the relay current will be harmonics due to the arc. It would appear that if harmonics were introduced by such an arcing fault in any appreciable magnitude, the relay would fail to trip. Since the paper states that the relay has been thoroughly investigated we believe that the paper would have been made more interesting if pertinent data representing cases of arcing faults had been presented.

The figures showing the test conditions show rather simple wave forms. It is to be noted that an almost infinite variety of wave shapes are encountered in such a differential circuit, depending upon the quality of the current transformers, the amount of short-circuit current and the amount and time constant of the d-c transient. Of this tremendous variety of wave shapes to be encountered quite a considerable variation from the values given in table I will be found. We presume that the entire field of possible ratios between the fundamental and the various harmonic components have been explored. Such an investigation should have produced enlightening data to determine in the design just how effective the restraining electromagnet must be in order to prevent the relay from ever operating on through faults. Data showing the percentage of harmonics in the differential current, which will accomplish this purpose, would then determine the percentage of harmonics which could be allowed in the case of an internal fault, without causing the relay to fail to trip, the harmonics being intruduced either through arcing faults, or saturated current transformers.


G
NEUTRAL BUS
G.E. CO. GENERATOR
DIFFERENTIAL RELAY
SHAFT
EXCITER
GENERAL ELECTRIC CO. GENERATOR
200,000 KVA 16,500 VOLTS
3 PHASE 60 CYCLES 0.80 P.F.
7000 AMPERES 1800 R.P.M.
RESTRAINING COIL
OPERATING
COIL
MAIN
FIELD
FIELD
POT.
V
GROUND BUS
3 GENERAL ELECTRIC CO. AUTO-
TRANSFORMERS EACH RATED
66,667 KVA SINGLE PHASE
15,940-9530 VOLTS 60 CYCLES
22 N.
GROUND &
TEST SWITCH
EXCITER BUS
(SWITCH HOUSE)
GENERATOR NO.6
GENERATOR NO.5
GEN.NO.4
GEN.NO.3
GEN.NO.2
GEN.NO.1
F.C.
S
G
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7
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5
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2
■ O.C.B. CLOSED
□ O.C.B. OPEN
O.C.B. CLOSED FOR TESTS 1,2,3,& 4 OPEN FOR TESTS 5,6,7,& 8
O.C.B. OPEN FOR TESTS 1,2,3,& 4 CLOSED FOR TESTS 5,6,7,& 8
O.C.B. USED FOR CLOSING IN ON 3-PHASE SHORTS
O.C.B. USED FOR CLOSING IN ON SINGLE-PHASE SHORTS
S□ O.C.B. OPENED ON SHORT
G HIGH-SPEED GRAPHIC METER CONNECTION
V OSCILLOGRAPH VIBRATOR CONNECTION
22 N. & 22 S. FEEDER REACTORS:
7.5 PER CENT AT 38,000 KVA
3 PHASE 27,600 VOLTS
22 S.
GROUND &
TEST SWITCH

Figure 1. Short-circuit tests—number 7 unit, Hudson Avenue

R. L. Webb (Consolidated Edison Company of New York, Inc., New York, N. Y.): The authors have described a relay system which should develop to have many useful applications. It is judged, from the paper, that the relay has so far been applied only for bus differential protection, using a nonsensitive operating point of five amperes to avoid incorrect operations if a current transformer should become open circuited.

While such a relay should be applicable to bus protection in some instances, such as, where it is desired to use existing current transformers having imperfect or poorly matched accuracy characteristics under high-current conditions, it would seem that its most fertile field would be in the protection of rotating machines and transformers since high sensitivity is usually much more important in protecting such apparatus than in protecting busses.

The authors have pointed out some of the difficulties that must be overcome in applying differential protection to power transformers. We have come upon a type of phenomena found to exist in the secondary of current transformers used for generator differential protection which must also be taken into account when applying relays for this purpose. These phenomena make it appear that a harmonic restrained relay might easily be worked into a protective scheme for such a machine as this generator, but the restraint obtained from the harmonics would probably have to be quite high. It might be worth while considering the use of a small amount of fundamental restraint as well, when a relay of such sensitivity is built.

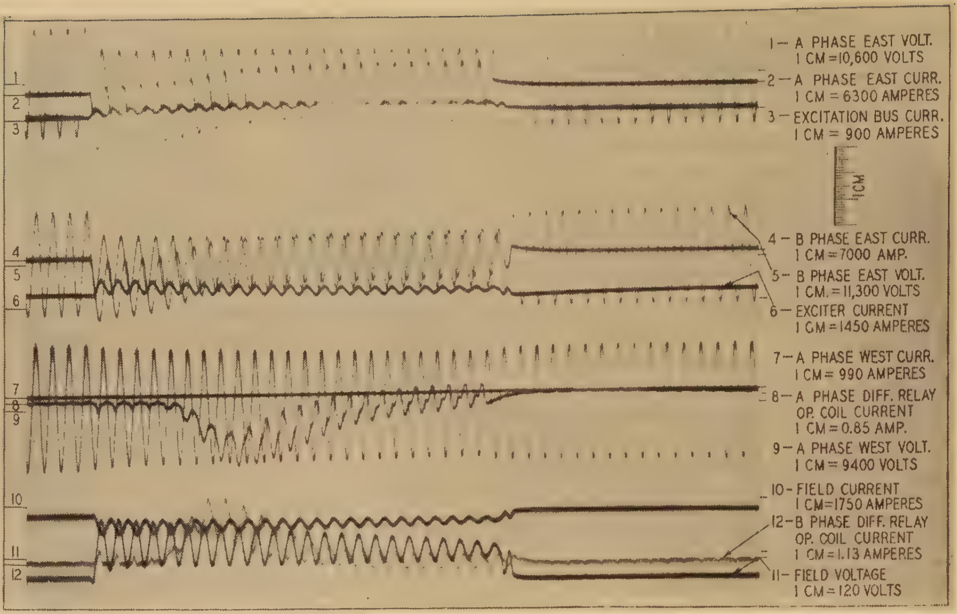

Figure 2. Number 7 unit short-circuit tests

A few years ago, some short-circuit tests were made on one of the later generators installed at Hudson Avenue Station. Oscillograph elements were connected into the operating-coil circuit of the percentage differential relays as a check on the current transformer characteristics for "through fault" conditions. Figure 1 shows the connections for the test. Both three-phase and single-phase faults were applied, beyond feeder reactors, with the machine operating alone at no-load and also when paralleled with the system and carrying a small percentage of rated load.

Figure 2 shows the results of the three-phase unloaded fault. Both *A* and *B* phase currents had a large d-c component. The effects on the *A* and *B* phase relay-operating-coil currents are plainly shown.

The results were similar to these for the single-phase-to-ground fault and for the tests made under light-load conditions.

In all of the cases, where the fault current had a large d-c component, it was noted that the relay-operating-coil current was rather high for a few cycles and had considerable 60-cycle as well as other frequency components in it. The current transformers, located in the generator neutral and at the bus breaker, though of different designs, have very good accuracy characteristics, at 60 cycles, up to 15 times rated current or more, and the current in these faults was only about three times the transformer ratings.

It is most probable that the d-c component in the fault current had different effects on the two types of instrument transformers involved and that this caused the appearance of the d-c component in the secondary current difference, as well as a healthy value of 60-cycle current with other harmonics. The late appearance of the d-c component in the secondary circuits is the basis for this assumption.

The relays in use, having a ten per cent differential operating characteristic with the usual type of current restraint, did not operate on these faults. If they had been a little more sensitive they might have functioned.

In any case, the use of harmonic restraint, even if some fundamental restraint must be added, should permit the use of relays having greater sensitivity than present ones and thereby give us more complete protection for machine windings.

G. B. Dodds (Duquesne Light Company, Pittsburgh, Pa.): The relay described in this paper should prove a useful addition to the protective-relay family, although some of us may prefer to use the standard percentage differential relays where applicable, for a while until we learn more about the harmonic restraint advantages and limitations.

As has been mentioned before, some of us have been wondering whether one-cycle relays are always desirable, and whether there is not frequently a desire for a two- or three-cycle delay. Of course, this can always be obtained by an interposing auxiliary relay.

In figure 7 is shown an oscillogram of fault current and differential relay current on a through fault. The fault current in this oscillogram is far from completely offset, and we are wondering whether tests were made with completely offset waves under this same current transformer and relay setup. From tests we have made, completely offset fault current adds enormously to the current obtained in differential circuits.

While the five-ampere relay will prove satisfactory in many cases, there are also frequent applications where a relay with lower operating current would be desirable; for example, where it is desired to have a fast ground relay in the neutral of the current transformers which must carry the magnetizing inrush to a large power transformer. In cases where the current-transformer ratio is large due to the size of the power-transformer bank, a one-half-ampere pick-up would be desirable. In other cases, where fairly sensitive ground protection is desired and there is danger of obtaining current by asymmetrical through fault currents, a harmonic-restrained relay with one-half ampere to one ampere sensitivity would be very useful.

T. W. Trice (Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md.): The introduction of a high-speed differential type relay unaffected by transients would indeed be welcomed by relay engineers. Methods heretofore used to prevent incorrect differential-relay operation generally result in delayed clearing of faults under correct operation when compared with the standards and requirements of modern relay practice.

With differential-relay installations the need for high-speed operation becomes more and more desirable as the magnitude of fault current increases. For example, a bus assumes greater importance as the connected load, and hence the possible fault currents increase, but at the same time high-speed fault clearing is essential to prevent serious damage and reduce system disturbance. This is an unfortunate condition, for while a reduction in relay time becomes more desirable with increased fault currents, it is necessary to approach high-speed operation with caution because it is more subject to incorrect operation than the slower relay settings. This leads to certain comments with regard to the relay introduced by Messrs. Kennedy and Hayward.

With reference to part *C* pertaining to magnetizing inrush current in current transformers, the authors' statements seem to discount the fact that the current in the primary of a current transformer is determined solely by the load or fault current in the power circuit. The primary current in a series transformer is not determined by the excitation conditions as it would be in a power transformer connected across the line. In other words, a current or series transformer is subject to the magnetizing inrush current of the main circuit only and does not have a primary magnetizing inrush current of its own. Another statement in this paragraph—"the secondary current appears as a transformation of the primary current with the inrush current subtracted"—seems an obscure way of describing the fact that the secondary current of a current transformer is proportional to the primary current except when the primary saturates the core, in which case the inrush current above saturation cannot be reflected in the secondary. In view of this, we are somewhat in doubt as to just what the authors have in mind and would suggest that the phenomena associated with the so-called magnetizing inrush be clarified.

In the operating-coil circuit, tuned to pass fundamental frequency, within what limits of frequency will the circuit permit fundamental current to flow? While system frequencies are normally relatively stable, it is possible to have on the equipment or bus differentially protected, a frequency above or below normal, during or immediately following severe system disturbances, particularly if this part of the system has been separated. If the circuit is too sharply tuned, it is possible that the relays might remain inoperative on a fault occurring during this off-normal frequency period.

It is assumed that the relay is self-contained, not requiring field adjustments, all inherent parts being co-ordinated and assembled at the factory. However, the importance of reliability on differential protective installations dictates that relays used for this purpose should have periodic checking. In the case of a harmonic-restrained high-speed relay, it would seem of utmost importance to periodically reaffirm the effectiveness of the restraining circuit to prevent operation during transient conditions, particularly since the time of operation has been reduced to a minimum. While no difficulty should be encountered for checking correct operation on normal frequency, it appears somewhat difficult to check the restraining circuit to see that it continues to function properly on harmonic frequencies.

In this connection, some information as to the type of condensers utilized in the relay and the effect of temperature change and age on their performance should be of value. Furthermore, what effect will a condenser failure have on the operation of the relay? Having the relay completely inoperative under the condition of condenser failure, depending upon back-up relays for protection would seem to be more desirable than incorrect operation. If a faulty condenser could cause incorrect operation, there is even more reason why periodic checking of relays should be carried out. Likewise, a description of the rectifier used with information as regards its resistance to aging, is desirable.

It is believed that a relay of this type has a definite place in high-speed differential protection practice, particularly on new installations. However, it might be pointed out that there are many differential installations in use on systems throughout the country. From an economic standpoint, it would be highly desirable to modernize many of these installations by eliminating the delay features and reducing the over-all relay time. For this reason it is believed that attention should also be given to the development of a harmonic-frequency filter that could be externally connected to present differential relays.

E. L. Harder (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The satisfactory solution of a relaying problem involves the determination of a discriminating function or quantity which will adequately discriminate the desired trip conditions from the desired nontrip conditions, and then development of a relay element or structure which will respond to this particular quantity. These discriminating functions or quantities are of two general types. First are those which theoretically and practically separate the trip and nontrip conditions by a wide margin, preferably having zero value for the nontrip condition. Relays may then be built having corresponding operating characteristics and applied without any great amount of application effort. Ability to determine the necessary setting analytically is of considerable importance. The second type of quantity or function is that requiring statistical analysis to prove its ability to segregate the trip from the nontrip conditions. This empirical type of solution involves infinitely more application effort and proof of adequacy than the former. For it is necessary not only to show that in general a dividing line exists, but also to show for any individual application where that dividing line is. In other words, it is necessary to determine empirically at what value of the discriminating quantity the relay must be set.

In this particular instance the relaying quantity is of the statistical variety and consequently proof of its adequacy over the range of operating conditions is necessary. It will be of interest to point out the factors of variation affecting the proportion of harmonics present under various conditions. It is also important, as pointed out by the authors, that the relay does not actually respond to harmonics, as calculated from the wave forms by conventional methods, but rather has a response affected by harmonics but altered by the shock application thereof. The factors which would appear to affect the wave shape and hence operation of this type of element are as follows. Consider first factors tending to produce harmonics during internal faults (faults on the protected bus section).

1. The primary current wave shape. For internal faults harmonics may be accentuated by restriking arcs, system resonances, or circulation of harmonic currents between generators of dissimilar wave form. Such circulating currents may have high harmonic content.

2. Saturation of current transformers. During internal faults the largest harmonics would be expected with a critical degree of saturation, greater or less saturation resulting in lower harmonic content. The degree of saturation present is affected by the relay burden, length of leads, internal burden (or secondary leakage impedance) of the transformers, type of iron, iron section, length of iron path and turns, and the amount of a-c current and amount and duration of the d-c transient. These factors vary widely from one application to another.

The other condition of interest is that having maximum tendency to operate the relay when it should not be operated. This would require a differential current above the five-ampere setting with low harmonic content. Such a condition would be most likely to occur when heavy through faults cause a differential current in the relay but where saturation, and hence harmonics, are low. It may also occur at very severe saturation where the current transformers act nearly as air core devices over a fairly large part of each cycle. At intermediate saturations the restraint may be more favorable.

The root-mean-square of harmonics in columns 1 and 2 of table I are 14 per cent and 33.5 per cent. In view of this fairly close margin, for typical conditions, the margins under limiting conditions as mentioned would be of particular interest.

E. H. Bancker (General Electric Company, Schenectady, N. Y.): The conversion of an antagonist into an ally is an accomplishment worthy of remark. In this paper the authors tell how the aid of one of the chief obstacles to successful differential protection has been enlisted to bring about better performance. The inability of current transformers to maintain a constant ratio at high overcurrents has been a major hindrance to a wider adoption of bus differential relaying because it was feared that there was too great a hazard of losing busses for external faults.

It has been known for a long time that whenever current transformers saturate because of a d-c component in the primary current or because the a-c current is too large for the particular transformer with the particular burden, the magnetizing current is large and full of harmonics. D-c saturation produces a preponderance of even harmonics and a-c saturation chiefly the odd harmonics. It was also known that when the secondaries of several current transformers saturated to different degrees were differentially connected, the magnetizing current differences passed through the differential relay. It remained, however, for the authors of this paper to put these known facts to work for the good of mankind. The ingenious separation of differential currents into their fundamental and harmonic components and the use of the harmonic content for restraining operation make possible high-speed differential relaying without the attendant danger of unnecessary losing a bus or piece of equipment for some fault external to it. This marks another advance along the path that relaying usually follows, i.e., to recognize the peculiarities and limitations of associated equipment and despite them all, to provide the required protection and service continuity.

Time alone will tell what other uses will appear for the harmonic restraint principle enunciated here. One is immediately apparent, transformer differential protection, where the troublesome harmonics arise from saturation in the power rather than in the current transformer. The application of harmonic restraint to transformer differential relaying will avoid the difficulties now existing in the use of high-speed relays for this purpose. Magnetizing inrush may be rendered innocuous without impairing the speed or sensitivity of the protection. Similarly, sensitive generator protection may be retained without the danger of false tripping or external faults having a large and slowly decaying d-c component.

H. P. Sleeper (Public Service Electric and Gas Company, Newark, N. J.): There can be no quarrel with the contention of the authors that the use of standard differential relays will tend to give improper operation on either bus or transformer differential protection because of the saturation of the current transformers or the sustained high charging current when a transformer is energized. However, the writer believes that it may not always be necessary to install relays of the types described by the authors of this paper to prevent such improper operation.

When straight differential relays, as compared with percentage differential relays, are used for such protection, the common way to avoid such a difficulty is merely to raise the trip-current settings. The apparent difficulty became increased when percentage differential relays were introduced, since the pick-up of these relays with one side de-energized is usually considerably lower than the normal setting of a straight differential relay. The obvious remedy is to merely increase the trip setting under these conditions. This applies to both transformer and bus percentage differential relays and ordinarily can be done without danger of failure since faults requiring the operation of such relays usually involve high values of power, and the operation of the relay elements under such fault conditions are accumulative, thus assuring positive operation.

It is recognized that the above suggestions are expedients only to take care of undesirable operating conditions. One of the simplest methods of preventing improper operation of percentage differential relays used for bus protection is to make certain that there will always be power in at least one restraining coil. This means that sufficient restraining coils must be present in the relays or certain current transformers must be paralleled to effect this result.

There is certainly a field for a differential relay which will not trip out a transformer bank incorrectly due to the inrush of magnetizing current when energized and yet will operate correctly and instantaneously when the protected unit becomes faulted. No such relay is on the market, to the writer's knowledge, which will or can be made to completely fulfill these specifications. If this new relay meets these specifications, the writer will be the first to cheer.

Since no characteristic curves of these new relays have been presented in this paper, it is impossible to analyze their operation; but it is the writer's opinion that the proper use of restraining coils, as in the manner described above, may still be required with the harmonic current restrained relays described in the Kennedy-Hayward paper.

L. F. Kennedy and **C. D. Hayward:** We feel very gratified indeed at the amount of interest aroused by this paper as evidenced by the unusually large number of discussions presented. The subject is apparently one of live and widespread interest. Since some of the points discussed were mentioned by more than one individual we think it better to review the discussion by topics rather than by the individuals presenting them.

Several questions were asked regarding possible fields of application. There seemed to be a feeling on the part of some that the harmonic restraint relay is intended only for bus protection. While the particular relay application described in the latter part of the paper was one of bus protection, still it should be understood that the harmonic restraint principle may just as readily be applied to relays intended for any other form of differential protection. As a matter of fact, the idea was first conceived for transformer protection. The recent interest in and demand for better bus protection lead to its first practical application being made in that field.

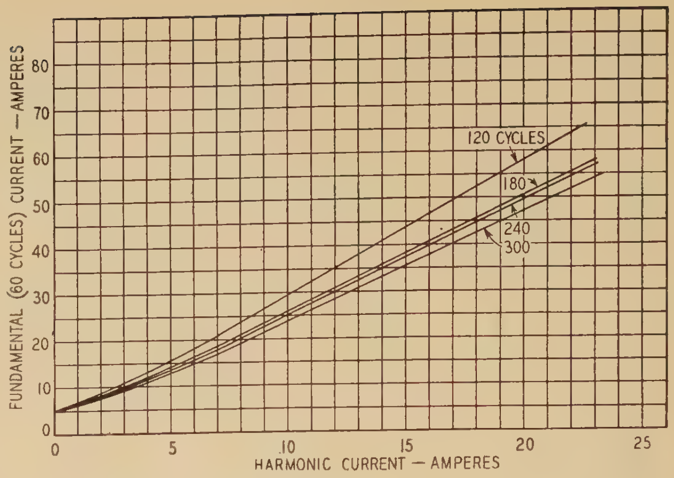

Figure 3. Harmonic-current-restraint characteristics of bus differential relay

Showing amount of fundamental-frequency current required to cause pick-up over the restraining effect of a given amount of harmonic-frequency current when the two are mixed in the input to the relay

Application to transformer and generator differential protection will require a relay having lower pick-up current than the five-ampere value required for the bus relay.

Some applications may require a certain amount of through current restraint in addition to the harmonic differential current restraint. This feature may be added by any of several means, for example, an additional restraining magnet energized by the through current might be used.

In regard to the question as to whether the high-speed operation is always necessary, we would like to give a very broad answer: If the reliability of a given type of protection is not impaired by high-speed operation, then high-speed operation is always desirable even though it may not be necessary. The necessity for high-speed operation usually arises from stability considerations but it is always desirable since it means reduced damage. We feel that with the harmonic-restraint principle the utmost reliability is obtained and that therefore the relay should be made to operate at as high speed as possible.

Several discussors asked for additional information on the operating characteristics of the relay, particularly as regards the percentage of harmonic restraint used and the effect of ordinary variations in the

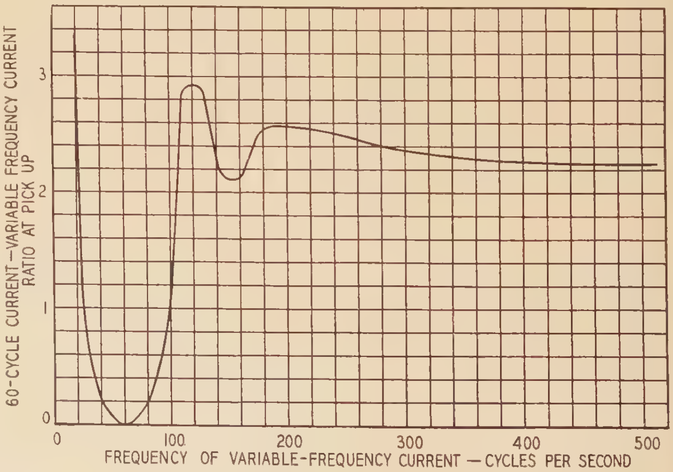

Figure 4. Restraint ratio versus frequency of current mixed with fundamental-frequency current

Slope of curves of the type shown in figure 3 plotted against frequency system frequency. This can best be shown by reference to two additional figures. The curves in figure 3 were taken by mixing a current of a given harmonic frequency with current of fundamental frequency in the input to the relay. For each value of harmonic-frequency current the amount of fundamental frequency current to cause pick-up was determined. Curves for the second, third, fourth, and fifth harmonics are shown. The similarity of these curves to the slope characteristic curves of the familiar percentage differential relay should be noted. A small difference in the slope of the curves for the various harmonics is apparent. This is due to the characteristics of the filter circuits employed in the relay as is better illustrated by figure 4. Here the slope of the curve, that is the ratio of fundamental current to harmonic current required for pick-up, is plotted against the frequency of the harmonic. The shape and height of this curve may be modified by design if occasion demands it. The curve is fairly flat at 60 cycles, indicating that small variations in system frequency will have negligible effect on the pick-up.

Periodic testing of the relay after installation to check the effectiveness of the harmonic restraint can be accomplished by passing current of a known harmonic content through the relay. Such a current is readily produced by means of a suitable small portable saturating reactor. A measure of the degree of restraint can be obtained by simultaneously passing a variable amount of sine wave current controlled by a rheostat through the relay coil, mixing it with the current produced by the saturating reactor and observing the proportion of the two at pick-up.

The capacitors used are of the "pyranol" type while the rectifier is of the copper-oxide-disk type. Both are of the best quality and are energized only momentarily when a fault occurs. Under these conditions exceptionally long life is anticipated. Any possible deterioration with age would, of course, be detected by the periodic tests.

The possibility of incorrect relay operation due to harmonics produced in the primary line current by various causes such as line oscillations, circulating currents due to differences in generator waveforms and arcing faults has been suggested. First of all, it should be appreciated that any harmonic present in the line current in the case of an external fault, even assuming it was not entirely cancelled out in the differential connections of the current transformers, can only produce a small additional restraining effect on the relay, which is not undesirable. It seems unlikely that any large amount of harmonic current will be produced in the differential circuit in the case of an internal fault by any of these causes. At any rate, the examination of many oscillographic records taken under a wide variety of conditions fails to show any noticeable amount present due to these causes after the first cycle. From this it would seem that the worst effect these harmonics could have would be to delay tripping for at most a cycle.

The successful application of the harmonic restraint relay requires knowledge of the relay characteristics and of the current transformer performance. At the present time, detailed information regarding the harmonics produced by various types of current transformers under all conditions is incomplete. A program of investigation is under way to obtain this information as quickly as possible. Until this information is complete applications will have to be made with unusual care and will therefore require individual consideration.

Some Schemes of Current-Limiting-Reactor Applications

By F. H. KIERSTEAD
MEMBER AIEE

CURRENT-LIMITING reactors are so detrimental to the normal operation of an electric system, and yet such a valuable contribution to its safety during short circuits, that it is very much worth while to try again and again to devise schemes which will use the ability of reactance to limit fault current and yet minimize the inevitable increase in regulation. With this in view, this paper reviews some well-known schemes of reactor application.

It is hoped that in exciting discussion, not only of the few schemes described here, but also of allied schemes, a trend toward better current-limiting protection may develop. This paper is written from the viewpoint of a designer, and the author realizes that application and operation engineers may find valid objections to the suggested uses of the schemes discussed. The author feels, however, that the chief value of the paper to the art will not be in its contents, but will be in the discussion it may excite.

The following schemes will be discussed:

A. Reactors shunted by circuit breakers.
B. The saturable-core reactor.
C. The split-circuit reactor.

A. Reactors Shunted by Circuit Breakers

In order to alleviate the difficulty of opening a faulted feeder, it has been proposed to use two circuit breakers in series, the one with a shorter time delay being shunted with a reactor, so that when it opens its reactance is automatically inserted in the circuit—thus lessening the duty on the second "main" circuit breaker. Such a scheme can be operated successfully and, therefore, the economic aspects of it will be discussed below.

The interrupting duty on a breaker shunted by a reactor depends, among other things, upon the amount of reactance in shunt. The duty is reduced by the shunt reactor to the extent that the voltage across the breaker is reduced below that which it would have been if the reactor had not been present—in other words, to the extent that the recovery voltage is reduced by the presence of the reactor.

In order to evaluate the reduction in duty on a breaker affected by a shunt reactor, let us compare two 60-cycle, 6,800-kva, 13.2-kv cable feeders—one equipped in the conventional manner with a circuit breaker and a three per cent reactor, and the other equipped, in addition to the above breaker and reactor, with a breaker shunted by a reactor. These two circuits are shown in figure 1 and the pertinent circuit constants are given below.

Generator reactance (X_G) = 10 per cent and 20 per cent reactance on 50,000-kva base.
Series reactor (X_R) = 3 per cent reactance on 6,800-kva base.
Shunt reactor (X_S) = 15 per cent reactance on 6,800-kva base.

The final recovery voltage across the breaker of the conventional feeder and that across the shunted breaker of the proposed feeder are given below:

Generator Reactance	10 per cent	20 per cent
	Final Recovery Voltages	
Breaker in conventional feeder	100%	100%
Shunted breaker in proposed feeder	77%	71%

This table shows that the breaker shunted by the reactor must, in the cases assumed, be approximately three-quarters of the capacity of the breaker in the conventional feeder. The shunt reactor was chosen large so that the series breaker which finally opens the circuit could have a low interrupting capacity. This breaker, however, must have sufficient capacity to carry the initial current until the shunt breaker opens. Of course, if the reactance of the shunt reactor were made less, the breaker which it shunts could have smaller capacity, but the series breaker would then have to have greater capacity.

The series reactor could, in some cases, be made smaller where a shunt reactor is used, but this would result in higher current to be interrupted, and consequently in shunt and series breakers of higher interrupting capacity.

The table below lists the equipment required for both methods. The interrupting duty of each breaker is given in per cent of that required for the breaker of the conventional feeder. The short-time current capacity of the series breaker is neglected in this comparison.

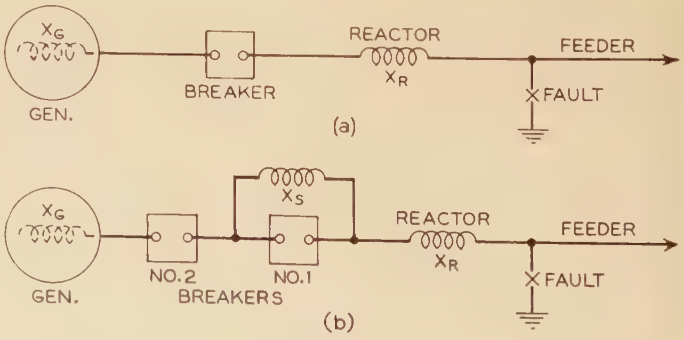

Figure 1

(a) —Diagram of the conventional feeder with a reactor and circuit breake

(b) -Diagram of feeder same as (a) except an additional reactor shunted by a circuit breaker

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Actually this consideration may call for a breaker approaching 100 per cent in size.

	Reactors		Breakers	
	Shunt	Series	Series	Shunt
Conventional feeder	No	Yes	Yes—100%	No
Proposed feeder	Yes	Yes	Yes—25%	Yes—75%

Since the proposed feeder requires an additional reactor and breaker, it appears to be more expensive than the conventional feeder.

Considering the use of the "proposed feeder" from the standpoint of regulation, the series reactor might be reduced and thus improve the regulation. This would, of course, increase the current to be interrupted and, therefore, increase the required capacity of both the shunt and series breakers. The same reduction in the series reactor, and hence the same improvement in regulation, could be obtained in the conventional feeder by the use of a larger circuit breaker. It would appear that the same improvement in regulation would entail about the same increase in cost in each scheme, and that the conventional scheme would have the lowest cost in any case.

There seems to be no economic justification for the "proposed feeder" from either the viewpoint of cost or improvement of regulation.

There does, however, appear to be a very limited application for a circuit breaker shunted by a reactor in the case of a substation where the short-circuit kilovolt-amperes has grown beyond the capacity of the feeder circuit breakers. The feeder bus can be sectionalized from the source of power by a large breaker shunted by a reactor, and all the feeder breakers interlocked with the large breaker so that they cannot open until the large breaker opens, and then the breaker on the faulted feeder interrupts the fault current, which has been reduced to the capacity of the breaker by the insertion of the reactor.

Before such an application is made, thorough consideration should be given to the following factors:

1. Have the existing feeder breakers sufficient short-time current capacity?

2. Is the increased time required to open two breakers in succession (instead of one) with the consequent liability of greater destruction at the fault justified?

3. Is there greater liability of motors on the other feeders dropping out of step due to the longer time before the short is cleared?

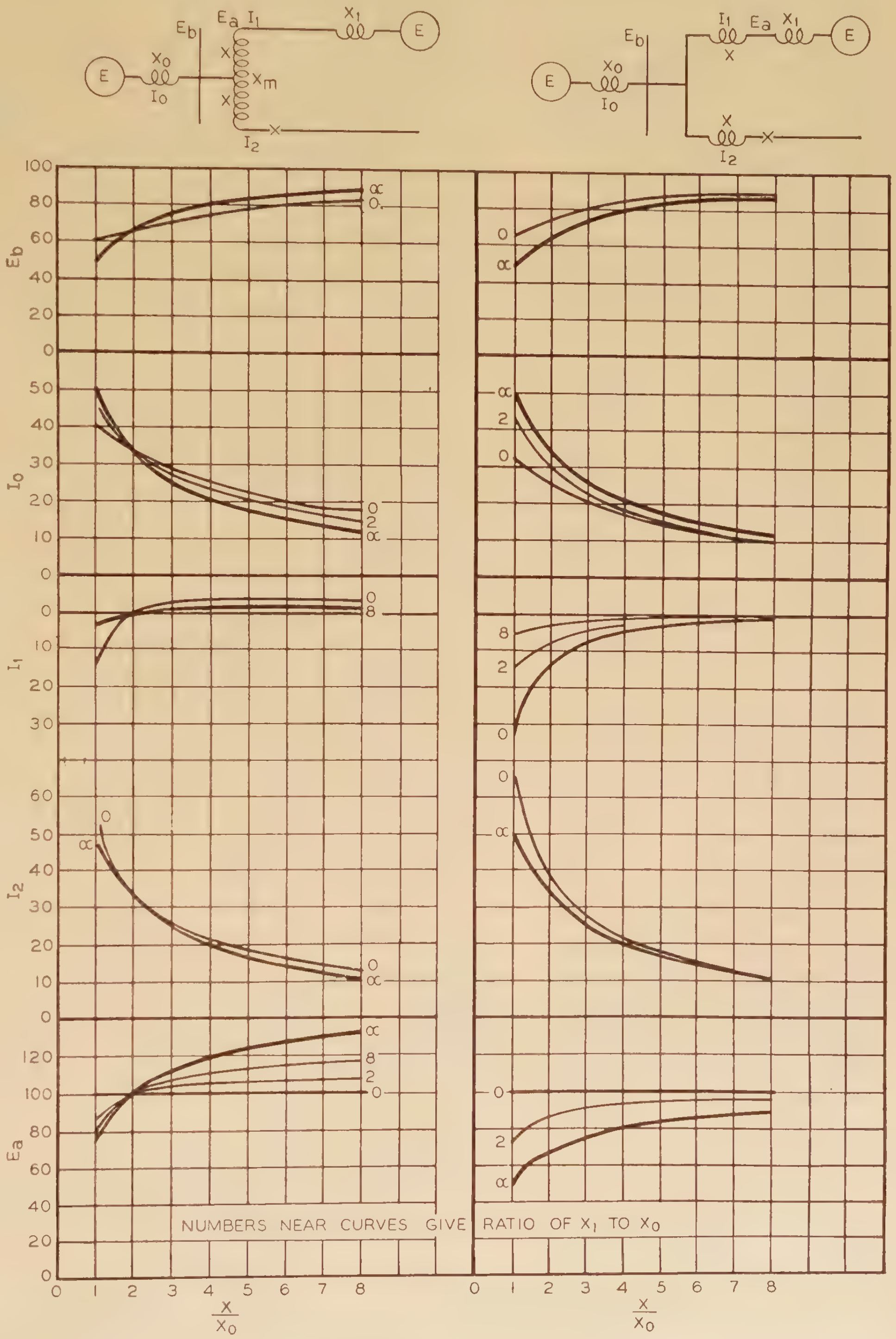


Figure 2. Comparison between split reactors and conventional reactors for feeder circuits. Feeders interconnected to other sources of power

In general, higher interrupting capacity breakers are a better solution.

B. The Saturable-Core Reactor

The inherent characteristic of an iron-core reactor is just the reverse of the desirable characteristic for short-circuit protection, in that its reactance *decreases* as the current increases. This defect of the simple iron-core reactor may be overcome by superimposing a d-c excitation[1] so as to displace the saturation curve in such a way that the reactance over the working range will *increase* with an increase in a-c current.

A properly designed saturable-core reactor operates very satisfactorily as a current-limiting reactor. Under normal operation it will insert from 10 per cent to 15 per cent reactive drop, and will limit short-circuit current to from 250 per cent to 350 per cent of normal.

The reactance at normal current is higher than is usually desired for feeder reactors, causing too high regulation drop, but may not be too high for bus reactors. The low short-circuit current permits the use of inexpensive circuit breakers of low interrupting capacity.

This type of reactor is inherently expensive for the reason that the core must be large enough to prevent the a-c flux from saturating it when the reactor is absorbing full circuit voltage. The winding must carry continuously the normal current—hence, the reactor will have a kilovolt-ampere rating of the same magnitude as the load. Since the reactor has two windings, one for alternating current and one for direct current, it is equivalent to a transformer of the same kilovolt-ampere rating as the load. In order to compare this type of reactor with the conventional air-core reactor, assume that the load transferred through the reactor is 30,000 kva. The saturable-core reactor would be equivalent in size and cost to a 30,000-kva transformer. If air-core reactors were used they would have 10 per cent to 15 per cent reactance, and since they have no iron core their physical

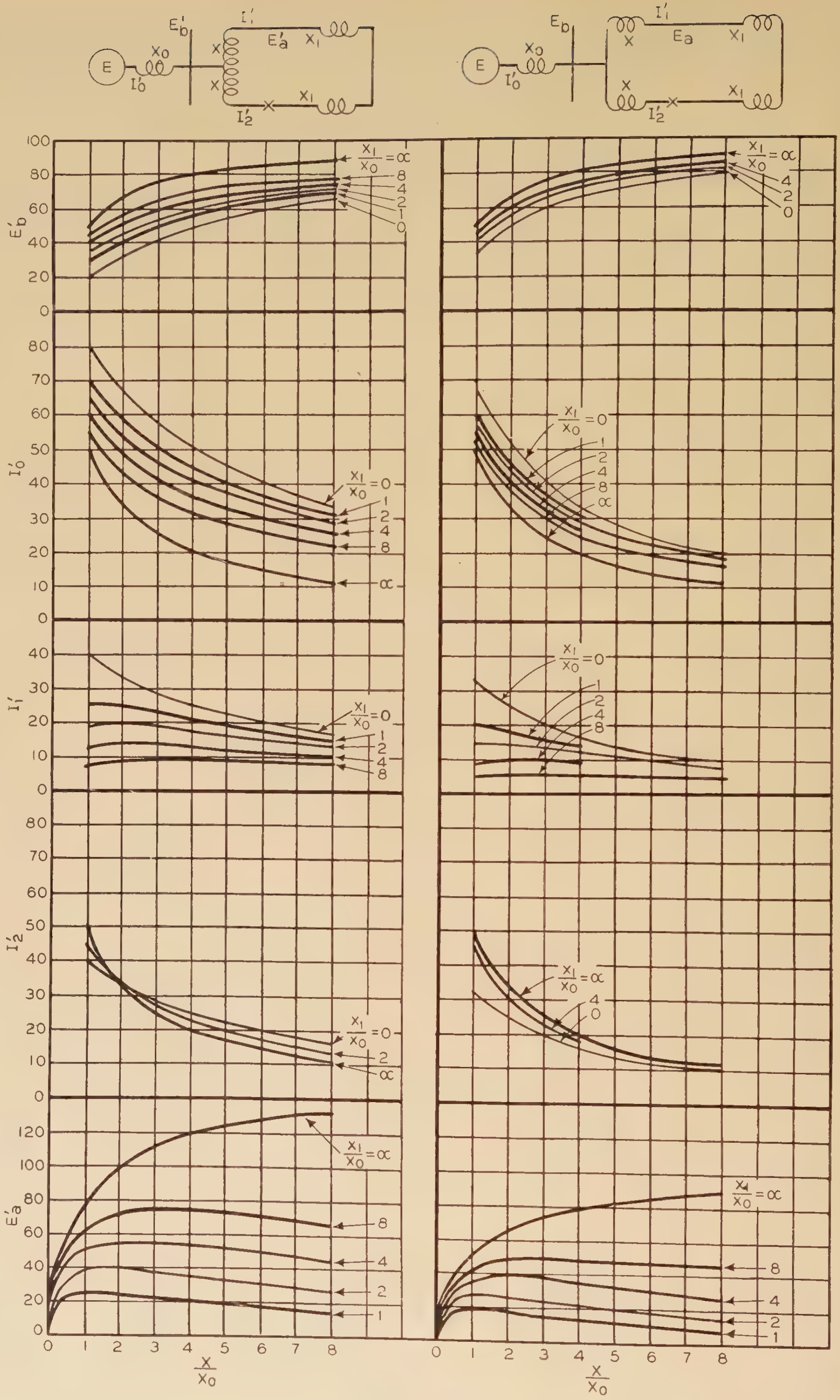


Figure 3. Comparison between split reactors and conventional reactors for feeder circuits. Feeders connected to same substation

size, and therefore their equivalent rating is based on the normal operation. Their rating would, therefore, be 3,000 kva. Since reactor kilovolt-amperes cost much less than transformer kilovolt-amperes, it is clear that a saturable-core reactor costs many times more than an air-core reactor. It is, of course, true that the circuit breaker used with a saturable-core reactor would cost much less than that used with an air-core reactor, due to the reduced short-circuit current. The reduction in circuit-breaker cost has not in the past been commensurate with the increased cost of saturable-core reactors, and for this reason they have not found a field of application as current-limiting reactors.

C. The Split-Circuit Reactors

The split-circuit reactor consists of two reactors placed so closely together that the reactance of one (due to mutual reactance) is affected by the current in the other. When used as current-limiting reactors they are connected so that with normal current in each reactor, their reactance is less than with current in only one. It is expected that under short circuit the current in the reactor connected to the fault will be very much greater than that in the other and, as a result, the reactance will be substantially greater at short circuit than at normal operation.

In some cases the current in the reactor not connected to the fault may be reversed in direction due to the fault, resulting in making the reactance of each reactor greater than if operating alone.

The reactors are usually wound as one continuous coil with a terminal brought out from the middle of the winding. The normal current is brought from the source of power to the middle terminal and divides, and part goes to each end terminal.

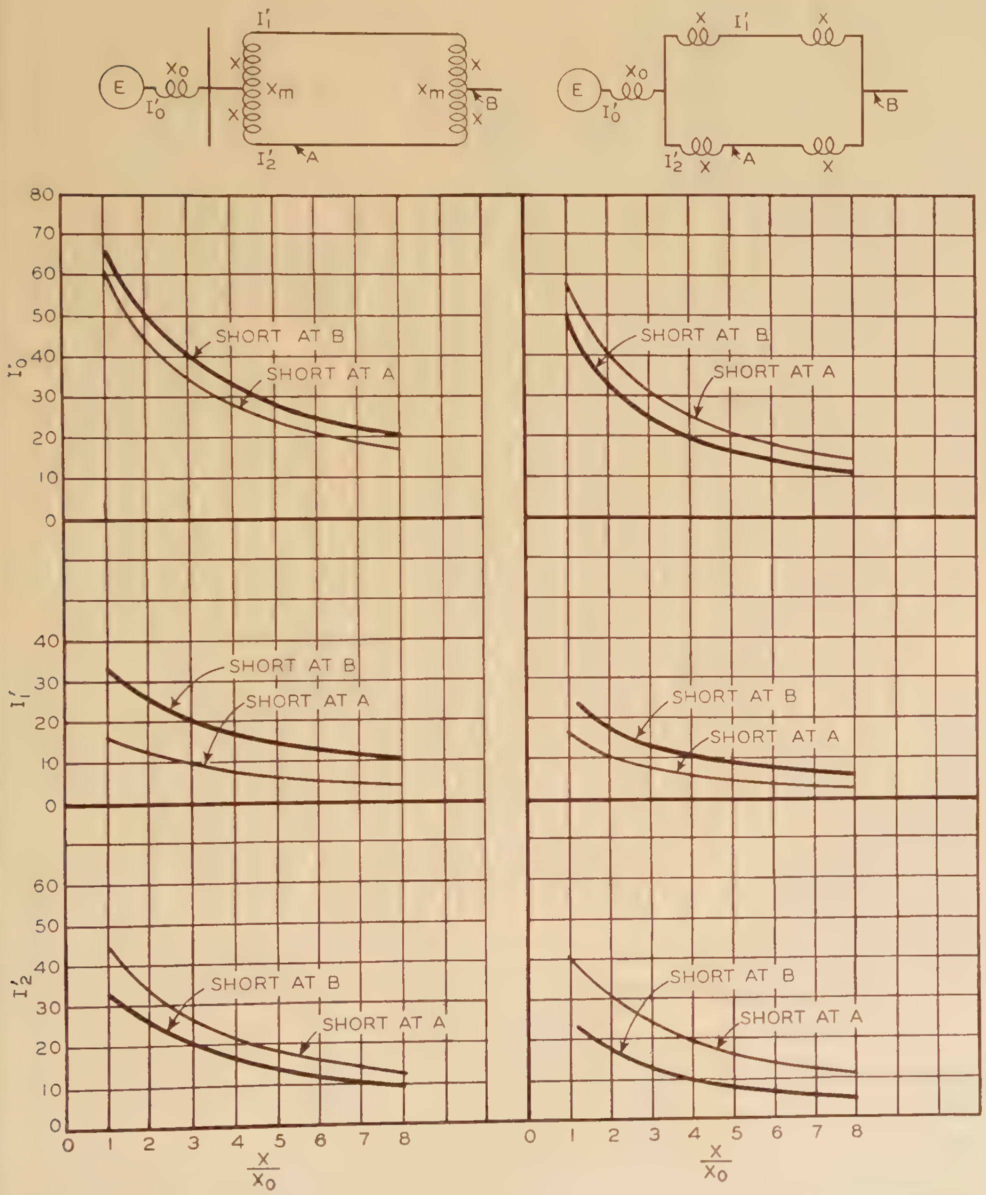


Figure 4. Comparison between split reactors and conventional reactors for feeder circuits. Feeders connected to same substation and reactors identical at each end

In the case of feeder reactors, it would be very desirable to separate the two coils from each other so as to fully insulate one from the other. This would permit placing a circuit breaker between the reactor and the bus. This, however, very materially reduces the mutual reactance and does not appear to be economically feasible in the dry type reactors, but could be done in a liquid-insulated reactor where the insulating distances are so much less.

In the dry-type reactors 50 per cent mutual reactance is about as high as is practical, while in the liquid-filled reactor the mutual may be somewhat higher.

The reactive drop across one section (one reactor) is equal to the current in that section times its reactance, plus the current in the other section, times the mutual reactance. The mutual adds, if the direction of the current in one section is positive compared to the current in the other section, and subtracts if negative. With the mutual reactance 50 per cent of the self-reactance, the resulting reactance of a section is 50 per cent with equal opposing currents, and 150 per cent with equal boosting currents.

With both sections carrying opposing currents, the

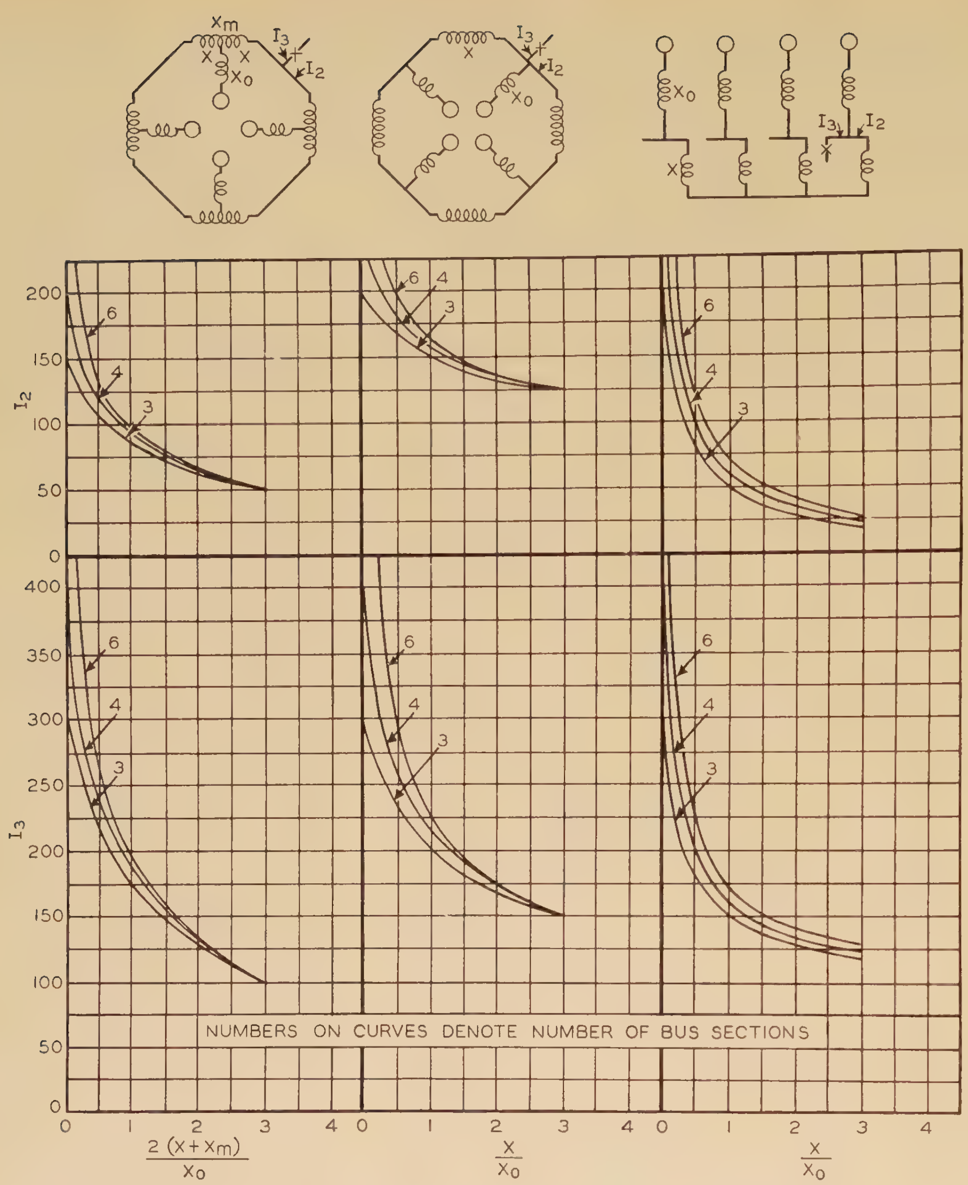


Figure 5. Comparison of split-reactor ring busses with conventional reactor ring and synchronizing busses

magnetic forces between the two sections are repulsive, and may be very great if the circuit is such that the two sections can carry opposing short-circuit currents. Therefore, in general, split circuit reactors must be very strongly tied together to prevent them from being expelled apart by the magnetic force incident to short circuit.

Due to mutual reactance, current passing through one section causes reactive rise in voltage on the other section which may be serious, and therefore must be considered.

There are two general cases for split reactors:

1. For feeder circuits.
2. For bus sectionalizing.

1. Split Reactors for Feeder Circuits

Three general feeder circuits have been considered as is shown in figures 2, 3, and 4.

The values given by the curves for the split-reactor feeder have been calculated from the formulas given below. These formulas are simple algebraic expressions, and the insertion of their proofs here is not considered warranted. The calculation of the curves for the conventional feeder reactors made use of standard formulas and are not given.

The value of mutual reactance used in all these calculations was 50 per cent.

The formulas 1 to 5, inclusive were used in calculations for split reactor feeders in figure 2.

Calculations for the split-reactor feeders shown in figures 3 and 4 made use of formulas 6 to 10, inclusive.

$$I_1 = \frac{X_m - X_0}{A + B} \tag{1}$$

$$I_2 = \frac{X + X_1 + X_0}{A + B} \tag{2}$$

$$I_0 = \frac{X + X_m + X_1}{A + B} \tag{3}$$

$$E_a = (I_2 - I_1)(X + X_m) \tag{4}$$

$$E_b = I_2 X - I_1 X_m \tag{5}$$

Where all reactances are reactive voltages across the reactors with a base kilovolt-amperes passing through them expressed in per cent of rated voltage.

$$A = \frac{X(X + X_1) + X_0(2X + X_1)}{100}$$

$$B = \frac{X_m(2X_0 - X_m)}{100}$$

Sketch of connections is shown in figure 2.

$$I_1' = \frac{X + X_m}{A + B} \tag{6}$$

$$I_2' = \frac{X + X_m + X_1}{A + B} \tag{7}$$

$$I_0' = \frac{2(X + X_m) + X_1}{A + B} \tag{8}$$

$$E_a' = I_1' X_1 \tag{9}$$

$$E_b' = I_2' X - I_1' X_m \tag{10}$$

Sketch of connections is shown in figure 3.

The curves are plotted against X/X_0 and X_1/X_0. The current values taken from the curves should be divided by the actual value of X_0. The values of voltages taken from the curves are correct for all values of X_0.

The reactances are all given as a percentage of rated voltage due to a base power flowing through them. The currents are given as the number of times the current of the base power can be divided into them.

An examination of these curves shows that the amount of feeder reactance (X) must in general be greater for the split reactor than for the conventional reactor; however, with equal currents in both sections, the effective reactance is equal to the self-reactance minus the mutual reactance, and since the mutual is 50 per cent, the effective reactance is only half of the self-reactance. This is considerably less than that required by the conventional reactors to limit the fault currents to the same values.

The mutual reactance helps to balance the load in parallel feeders due to raising the voltage on the underloaded feeder and lowering it on the overloaded one.

Whether or not there is sufficient merit in the split reactors to warrant their use in particular feeder circuits depends on the individual characteristics of the system and on the value that can be ascribed to reduced regulation in the particular system.

With these factors known, the curves make a rapid comparison possible. The circuits shown in figure 4 are particularly favorable to split reactors.

The case of split reactors for feeders may be stated as follows:

The advantage of lower regulation and better division of load between the parallel feeders must adequately balance the following disadvantages:

1. Higher cost due to a larger reactor and to the additional expense of supporting it to resist high repulsive forces.
2. Rise in voltage (E_a) which may be appreciable, as is shown in figure 2, if feeder reactance (X_1) is high.
3. The necessity of using liquid-filled reactors if circuit breakers must be placed in the individual feeders between the reactors and the bus.

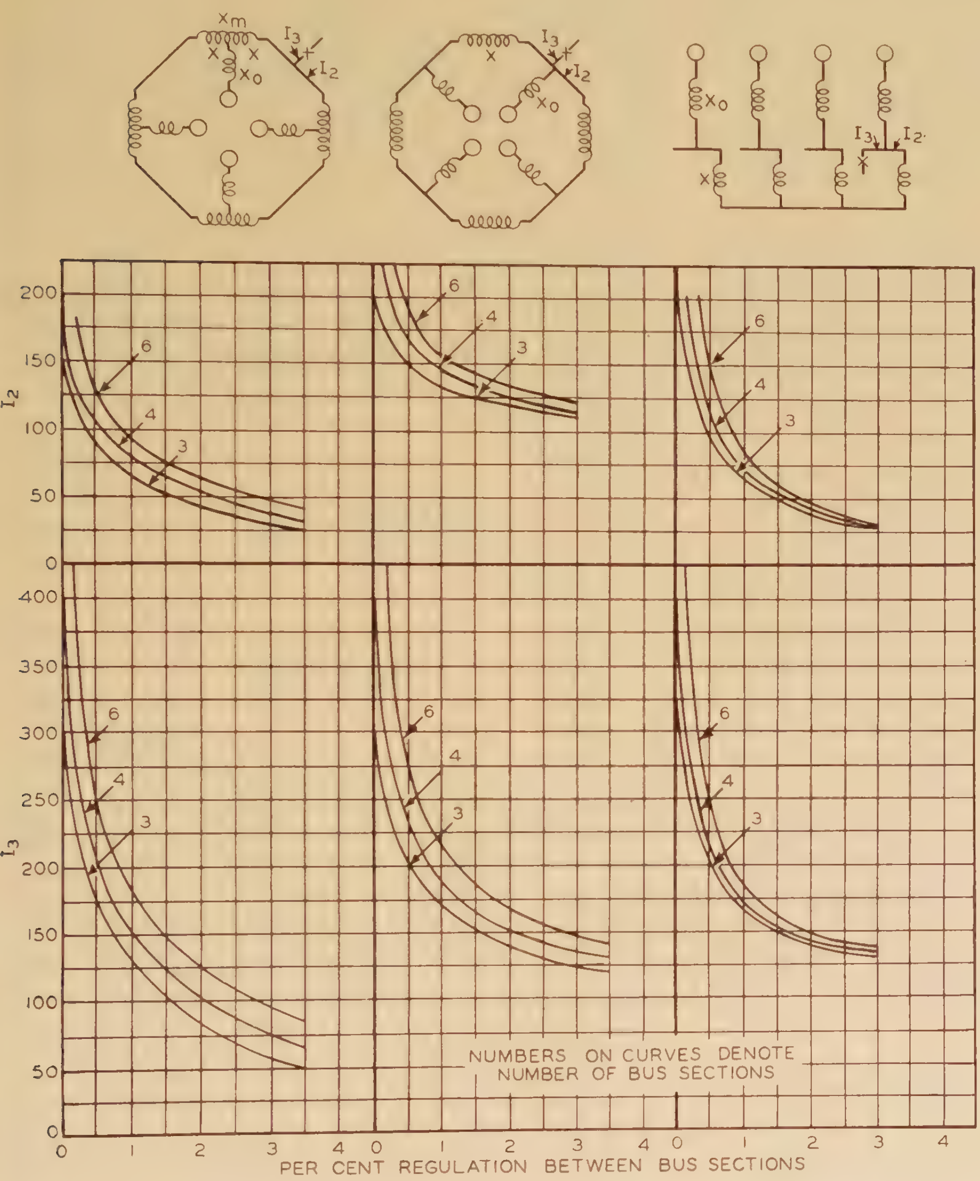


Figure 6. Comparison of split-reactor ring busses with conventional reactor ring and synchronizing busses based upon $X_0 = 1$ and $X_m = {}^1/_2X$

2. Split Reactors for Bus Sectionalizing

In order to ascertain if the split reactor has any value for bus sectionalizing, its use in ring busses has been compared with conventional reactors in ring and synchronizing busses. The split reactor is not suitable for use in synchronizing busses.

In figure 5 the ratio of bus reactance to generator reactance is plotted against short-circuit currents for the split-reactor-ring bus, the conventional ring bus, and the conventional synchronizing bus. Three, four, and six bus sections are included. The curves are based upon one per cent generator reactance. In practical cases the generator reactance is of course always greater than one per cent, and the correct short-circuit current is obtained by dividing the current values taken from the curves by the generator reactance. The split-reactor curves are based on $X_m = {}^1/_2X$.

In figure 6 short-circuit currents are plotted against the regulation due to load transfer. The calculation of the regulation is based on the following conditions:

1. That the kilovolt-ampere supply connected to each bus section is equal.
2. That the kilovolt-amperes transferred to one bus section from

all the other bus sections is equal to the kilovolt-ampere supply connected to one bus section. This means that the load on one bus section is equal to the kilovolt-amperes connected to two bus sections.

3. That these bus sections each contribute an equal amount of the transferred kilovolt-amperes.

4. The regulation is the reactive drop between extreme bus sections due to the load transferred.

5. That the reactance is the per cent of normal voltage across the reactance with the kilovolt-amperes of one bus section passing through it.

The formulas for the calculation of the regulation are given below:

Number of Bus Sections	Regulation Drop		
	Split-Reactor Bus	Conventional Ring Bus	Conventional Synchronizing Bus
3	$X + X_m$	$0.5X$	$1.5X$
4	$1.33\ (X + X_m)$	$0.667X$	$1.33X$
6	$1.80\ (X + X_m)$	$0.9X$	$1.2X$

In the curves in figure 6 the regulation between extreme bus sections is plotted against short-circuit current. The curves are based on a generator reactance of one per cent. The current values taken from the curves must be divided by the generator reactance, and the regulation values taken from the curves must be multiplied by the generator reactance.

The following examples will show how the curves may be used.

Suppose a six-section bus is to be used and I_2 (see diagrams in figure 6) is to be limited to nine times normal current of one generator and the generator reactance is 15 per cent. The regulation between extreme bus sections and the bus reactance is required. Referring to figure 6 and entering curves with current value of $9 \times 15 = 135$ (because curves are based on one per cent generator reactance), the split-reactor bus curve for six sections gives a regulation value of 0.49, which has to be multiplied by 15, giving a regulation of 7.35 per cent. The through reactance, $2(X + X_m)$, of the bus reactor obtained from the regulation by use of the regulation formulas is 8.18 per cent. By the same procedure it is found that with the conventional ring bus the regulation is 30.0 per cent and the bus reactance is 33.3 per cent. With the synchronizing bus the regulation is 9.0 per cent and the bus reactance is 7.5 per cent.

It should be noted that figure 6 gives a true comparison of relative short-circuit currents and regulation irrespective of the reactance of the generator, because the same reductions have to be made for varying values of generator reactance for all three bus schemes.

Since the reactance of generators will always be larger than the mutual reactance of the split reactor, the bus voltage will not rise above normal.

Figure 6 shows that the split-reactor bus has a marked advantage over the conventional ring bus. A comparison with the synchronizing bus is much more difficult because the two schemes are quite different. In addition to the currents shown on the curves, consideration must be taken of the short-circuit currents on the synchronizing bus itself, as these currents are very large. In many cases, bus reactance sufficiently high to limit fault currents on the synchronizing bus to safe values may make the regulation so high that the synchronizing bus scheme is difficult to operate.

The author realizes that the choice between these schemes depends a great deal on the individual conditions of particular stations, and has given these curves to assist in making the choice. The curves indicate that the split reactor bus should be given thoughtful consideration.

Summarizing

1. It has been shown that reactors shunted by circuit breakers do not have a general application. A very careful study may reveal limited applications in which a feeder bus of a substation is connected to the source of power through a reactor shunted by a large breaker, the large breaker being so interlocked with the feeder breakers that it has to open before any of the feeder breakers can open.

2. Saturable-core reactors have not yet found a field of application as current-limiting reactors because of their very high cost.

3. Split reactors show advantages over the conventional reactors for feeder circuits, and particularly for lines with reactors on each end. They have a substantial advantage over the conventional reactors for ring busses. The possibilities of their use warrants careful study.

Reference

1. Theory of D-C Excited Iron Core Reactors and Regulators, A. Boyajian. AIEE Transactions, volume 43, 1924.

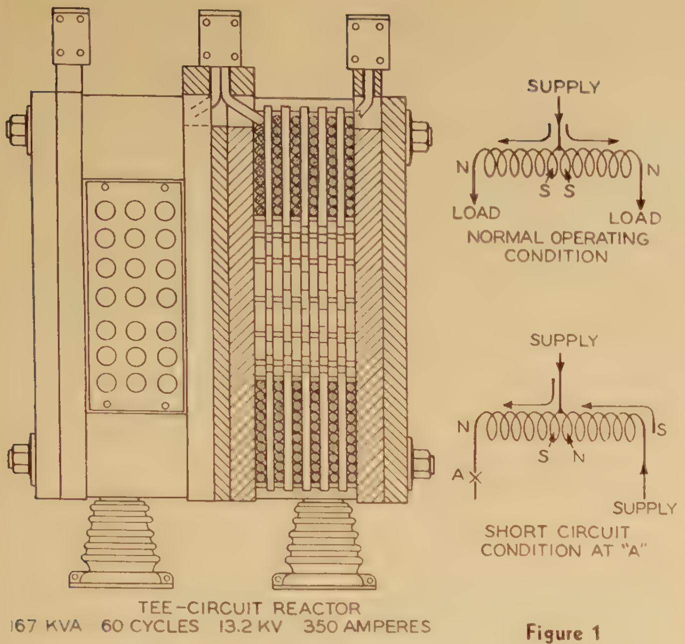
Discussion

J. A. Elzi (Commonwealth and Southern Corporation, Jackson, Mich.): This paper is interesting to the application engineer in that it deals with the problem of providing sufficient reactance in a circuit to limit the fault current to a desired value without at the same time introducing excessive voltage regulation for normal load conditions. The engineer is usually tempted to try various schemes of connections to accomplish this, and the paper demonstrates the necessity of making a careful analysis of the results which can be obtained by using various reactor connections and designs.

The conclusions given in the paper regarding the advantages of split reactors for feeder circuits where there are reactors at each end of the feeders seem quite logical, but the curves presented in figure 4 do not appear to demonstrate this. For a given set of reactance values, the currents I_0', I_1', and I_2' apparently are all greater for the split-reactor scheme than for the conventional-reactor scheme. This is to be expected for faults at B but not for faults at A. It may be that the curves are not being interpreted properly and an example similar to that presented for the six-section bus of figure 6 would be helpful in clearing up this point.

S. I. Oesterreicher (Metropolitan Device Corporation, Brooklyn, N. Y.): Due to first cost, complications in circuit arrangement and control in scheme B, as well as greater space requirements for scheme A, there are, no doubt, good reasons from the operating standpoint for objecting to these two schemes as described in Mr. Kierstead's paper.

However, the tee-circuit reactor—also known by the names of split- or twin-circuit, double or bifurcated reactor, has certain operat-



TEE-CIRCUIT REACTOR
167 KVA 60 CYCLES 13.2 KV 350 AMPERES

Figure 1

ing characteristics for which it should in the future receive greater popularity than during the past.

Much of the distrust toward the tee-circuit reactor is due, no doubt, to some shortcomings of early designs. After correction, it functioned in accordance with the intent of its inherent characteristics. Some of these later tee-circuit reactors have over 12 years of satisfactory operating record to their credit.

As stated by Mr. Kierstead, the advantage of this type of reactor is that during normal operation the voltage drop across the reactor is reduced by the amount of mutual inductance between the two windings. During short circuits the subtractive mutual inductance becomes additive, and thus the reactance through each coil half increases and there is automatically a greater amount of short-circuit protection inserted into the respective circuit.

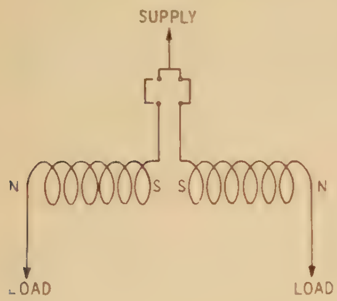


Figure 2. Tee reactor for two independent circuits

Unless there is a simultaneous short circuit in both load legs of the reactor, the reactance value through the reactor will always be greater during short circuits than during normal operation. This is true even when one of the two circuits is open beyond one of the reactor load side terminals.

While simultaneous short circuits in both reactor legs are exceptions from normal rule, nevertheless, the reactor has to be designed for just such emergencies. The repelling forces between the two halves during such short circuits, especially with such high mutual inductance values as Mr. Kierstead assumed in his calculations, may reach well into hundreds of thousands of pounds. I presume this value was assumed to illustrate the advantages of the *T* reactor to its fullest extent. The mutual inductance in our coils was limited close to 30 per cent.

I believe the *T* reactor would have its greatest field of application on secondary distribution feeders up to the five-kv range. In these circuits as little as possible reactance would be most welcome from the standpoint of regulation. With increase in generating capacity and load, the usually inexpensive breakers on these circuits would require greater protection during shorts, which could be readily provided by the *T* reactor. The reactor being compact, takes less space, is lighter, and does not cost more than two single-phase coils. To eliminate the disadvantage of having two circuits out of service at the same time in case of disturbance on only one side of the *T* reactor, the two feeder circuit breakers may be placed upon the supply side of the circuit beyond the common terminal of the reactor. Beside the regular equipment of the two feeders this arrangement would require only one additional terminal upon the reactor.

P. N. Sandstrom and **E. L. Michelson** (Commonwealth Edison Company, Chicago, Ill.): This paper presents interesting data regarding the application of the split reactor on feeder circuits and for bus sectionalizing. Some time ago, it was proposed by the Commonwealth Edison Company to use the split reactor in a somewhat different manner, shown in figure 3*a* of this discussion. In this diagram, busses 1 and 2 represent the main busses in a large station; these busses are normally separated, but the split reactor can be used to connect a source of power to feed both busses simultaneously, and at the same time maintain a certain degree of separation between the two busses. In this way, it possible to obtain a low value of reactance between the source and the load, and yet have a high value of reactance between the two main busses in the station. It is recognized that this application is a special form of the feeder circuit described in the paper.

Figures 3*c* and 3*d* of the discussion show values of fault current corresponding to I_2 of figure 2 in the paper, for values of x/x_0 from 0

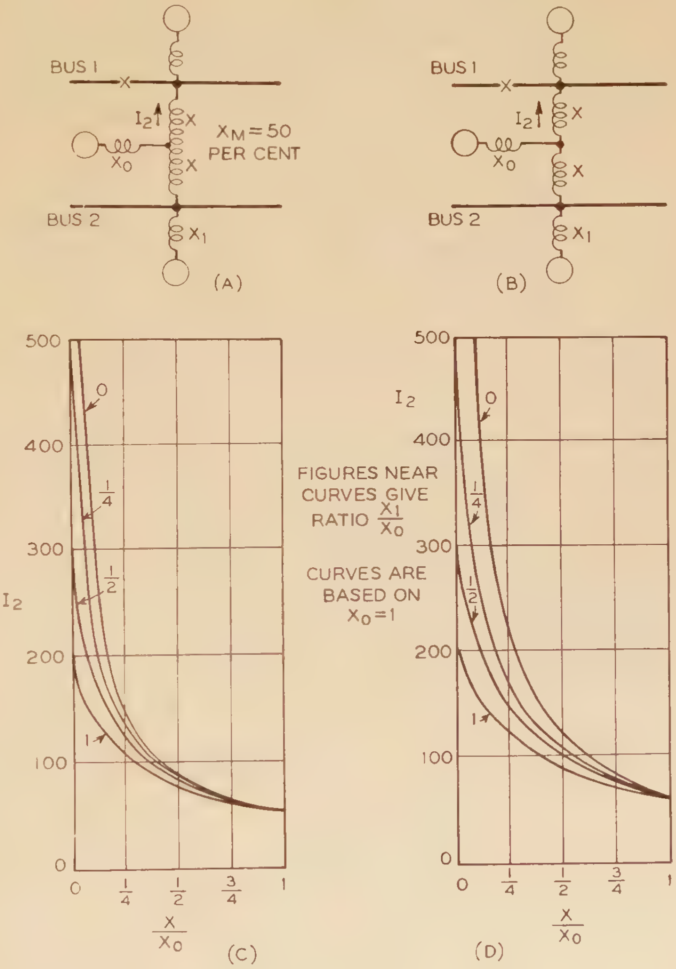


Figure 3

A—Split-reactor connection
B—Conventional design
C—Short-circuit currents with split reactor
D—Short-circuit currents with conventional reactor

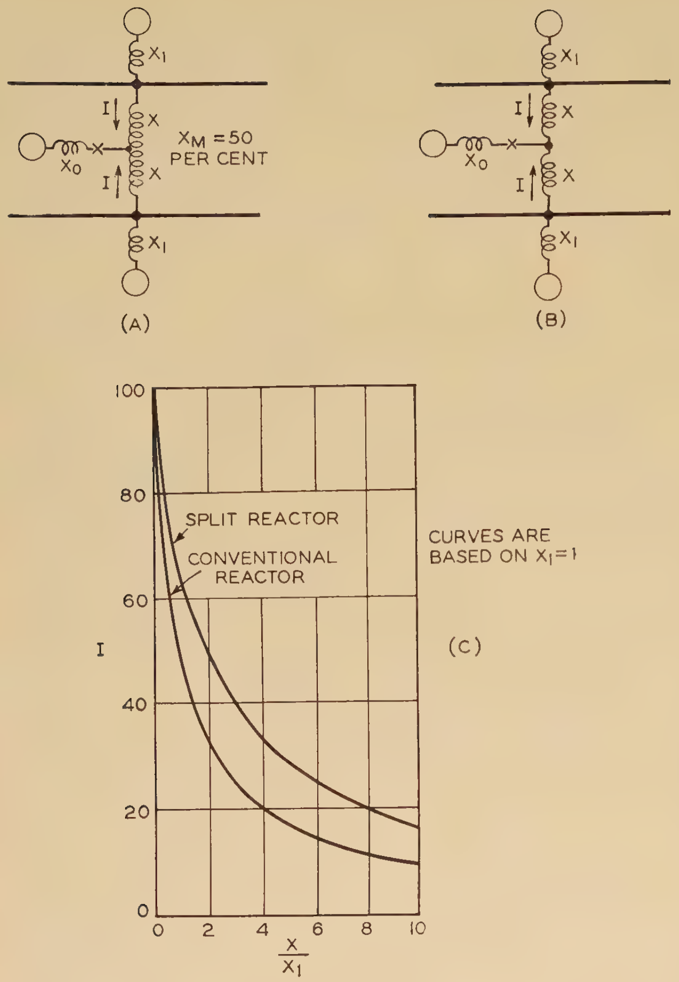


Figure 4

A—Split-reactor connection
B—Conventional connection
C—Short-circuit currents for faults shown in *A* and *B*

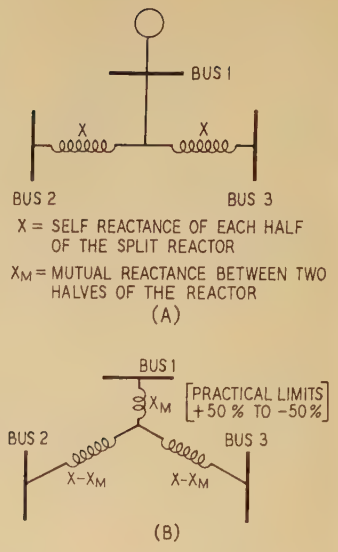
to 1. Figure 4 of the discussion shows the fault currents for faults in the source of power which feeds both busses. These curves in figures 3 and 4 show that for the same value of self-reactance, the split reactor gives a more effective separation between the busses than is obtained with the conventional reactor, but the use of the split reactor results in higher values of fault currents for faults on the source connected to the split reactor.

It would be interesting to know the comparative cost between the split reactor and the conventional reactor.

Figure 5 shows the equivalent circuit which can be used to represent the split reactor.

Figure 5

A—Split-reactor connections
B—Equivalent circuit for split reactor


BUS 1
X
X
BUS 2
BUS 3
X = SELF REACTANCE OF EACH HALF OF THE SPLIT REACTOR
XM = MUTUAL REACTANCE BETWEEN TWO HALVES OF THE REACTOR
(A)
BUS 1
XM
PRACTICAL LIMITS +50 % TO −50 %
BUS 2
BUS 3
X−XM
X−XM
(B)

In this circuit, X_M should be taken as positive if the mutual reactance has a positive effect; that is, if fault current in one circuit results in a drop in voltage on the second circuit. X_M should be taken as negative if the mutual reactance has a negative effect; that is, if fault current in one circuit results in a rise in voltage on the second circuit. This is in accordance with the accepted method for dealing with such circuits. It will be noted that this is contrary to the method used in this paper and in figures 3 and 4 of the discussion, since a negative mutual effect has been expressed as a positive quantity.

F. H. Kierstead: In accordance with Mr. J. A. Elzi's request, I wish to give an example covering a comparison of the split reactor with the standard reactor. In the split reactor assuming the reactance of one section (X) is four per cent and the generator reactance X_0 is one per cent, and a fault at A, the curves in figure 4 give $I_2 = 21.5$, $I_1 = 7.5$, and $I_0 = 28$. Since the mutual inductance is 50 per cent, the reactance to rated balanced load current is two per cent.

Referring now to the standard reactor, if its reactance (X) is 3.5 per cent and the generator reactance is one per cent and a fault at A, curves in figure 4 give $I = 21.5$, $I_1 = 6.5$, $I_0 = 27$. Reactance to rated balanced load current is 3.5 per cent.

Figure 3 of this discussion shows the advantage of the split type of reactor for a fault on bus 1, while figure 4 shows its disadvantage with a fault on the midpoint of the split reactor. These two curves show that the split reactor must be properly applied to obtain its benefits.

Mr. Oesterreicher shows practical applications of the split-type reactor. In the split-type reactor for independent circuits care must be taken that the two sections are insulated from each other for the full voltage, and if one of the circuits is taken out of service to be worked on, it must be grounded at both ends so that the mutual inductance does not induce serious voltages in the idle reactor.

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 13 pages appear discussions submitted for publication, and approved by the technical committees, on previously published papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

The Application and Performance of Carrier-Current Relaying

Discussion and authors' closure of a paper by Philip Sporn and Charles A. Muller published on pages 118–24 of this volume (March section), and presented for oral discussion at the relays and reactors session of the winter convention, New York, N. Y., January 25, 1938.

T. G. LeClair: For discussion see page 291.

R. M. Smith (Westinghouse Electric and Manufacturing Company, Newark, N. J.): While the paper by Messrs. Sporn and Muller deals primarily with the problems to be solved by the application of carrier-current relaying, we believe that some comments on the particular scheme of carrier relaying are worth while.

In reviewing the steps in the development of carrier relaying toward faster operation it is apparent that one outstanding contribution assisted in the realization of speeds in the order of one cycle. This improvement consisted in the use of a normally blocked trip circuit by the means of a receiver relay whose tripping contacts are normally open. This method of handling the carrier-operated blocking function was first used by the authors of the paper and I believe that due credit should be given them for this contribution to the development of carrier-current relaying.

One thing to be noted in the one-cycle scheme described is that the speed of clearing faults has been gained at the expense of reliability in blocking on external faults. This comes about, of course, from the use of circuit-opening contacts to remove carrier rather than circuit-closing contacts. This means that on quick reversals of power which occur on parallel lines and loop systems, carrier is stopped by a circuit-opening contact and established at the opposite end of the line by a circuit-closing contact. The opening contact will ordinarily beat the closing contact and there will be a short interval in which no blocking signal is present. The authors have circumvented this difficulty by the use of an additional temporary blocking relay. It is questioned whether this is good practice since an undesirable time delay will be introduced in clearing an internal fault which occurs immediately after an external fault. Would it not be preferable to slow up clearing times by, say, 0.25 to 0.5 cycle and use this much time interval as a definite margin of safety in blocking?

It is observed that the contacts which start carrier and the tripping contacts are on the same overcurrent element. This means that for external fault currents, which are near the minimum pick-up value of the relays, the relay at one end of the line may operate, while, due to different current-transformer characteristics, the relay at the other end may not operate. If the relay at the line end where power flows into the bus is the one which does not pick up, then a blocking signal is not sent to prevent unnecessary tripping at the other end. The obvious thing to do is to set both relays the same and considerably below the minimum fault current expected. On phase-to-phase faults it is generally not difficult to do this, but on ground faults where fault resistance or distance may limit the current to very low values, it may be very difficult to set the relay pick-up value below the lowest possible fault current. One solution of this trouble is to place the carrier start and tripping contacts on separate elements. The starter element can then be set considerably below the tripping element, thus assuring that whenever the currents for external faults approach the minimum pick-up value of the tripping element, they will be safely above the pick-up value of the carrier start element.

Since a three-phase directional element requires that the ground fault current be twice the magnitude of the load current, to indicate fault power correctly, there is grave possibility that the relay scheme, as described, will fail to clear internal ground faults involving low currents. Of course, this characteristic of the three-phase directional element has been encountered before on conventional relaying, but its seriousness in a carrier scheme is much aggravated because the failure of only one directional element to function will block both ends from tripping. We feel that single-phase directional elements for phase, and a separate ground directional element, are much more desirable in a carrier scheme. It may be argued that the single-phase element is liable to go wrong on a system with a multiplicity of ground points, or due to load currents, but this is taken care of by supervising the directional element through an impedance element and the use of a ground preference scheme as described in the paper by Harder, Lenehan, and Goldsborough, whereby on ground faults the ground relays can take command of the situation from the phase relays.

Messrs. Sporn and Muller have cited several of the advantages in the application of carrier relaying and have described actual examples of the applications which have served to bring out the specific features to be gained by the use of carrier relaying. The record of their experiences with this type of protection should be of great interest to system-protection engineers, as it demonstrates the reliability of the equipment in actual service. They have stimulated a great interest in this form of protection and their paper shows that from an operating standpoint their faith in this type of protection has been justified.

O. C. Traver (General Electric Company, Philadelphia, Pa.): I appreciate the frank exposition that Messrs. Sporn and Muller have made of both their sorrows and their joys in connection with a commendable pioneering work with carrier-current protection. To me the major interest is in table I where much more information exists than is at first apparent. I should like to analyze these figures in a search for the reason back of the authors' boundless faith indicated by their remarks at the end of section II concerning eventual "perfect performance."

In this review I will offer no alibi and only cold figures will be used, directly from table I without modification. I understand from the text that the heading "Operations on Internal Faults" might be more properly expressed as "Number of Internal Faults." As these were invariably cleared correctly, we can say that there were at least two correct breaker operations for each fault. I am therefore going to double all quantities given under that heading so as to approximate the number of correct operations for direct comparison with those that are incorrect. On the other hand, I will ignore the recorded 2,000 possible chances for operation as being of debatable concern.

Year Installed	Total Correct Breaker Operations	Total Incorrect Breaker Operations	Approximate Years in Service	Ratio Correct
1936	18	1	2	95 per cent
1937	12	0	$^1/_2$	100 per cent

Observe that the over-all ratio definitely and consistently *improves* with years of service, indicating that troubles with a given equipment are rapidly eliminated.

The installations of the last two years have not been in action long enough to show a trend.

But there is real comfort here again because it indicates that later days relays have been designed for this work, and we can now confidently expect to start from a higher plane at the very outset, and with the vision of such a prospect perhaps the authors are justified in looking forward to results which in comparison with their pre-carrier experience might not be improperly considered as "perfect performance."

The authors have told of having corrected certain troubles. Let us see what actual effect followed. We will admit that one may expect diffculties the first year or so, and then check results after these have had a chance to be ironed out. For example, the operating record for the years 1935, 1936, and 1937 for all relays installed in 1933 shows at least 74 correct operations and one incorrect. This gives 98.6 per cent correct operations, and for the speed involved that looks excellent. Even better is the entire record for 1937 with 96 correct and one faulty operation giving 99 per cent correct. But we won't confine ourselves to scattered illustrations. Maybe I just looked for good ones, so how about the rest of the figures?

If troubles met in the field are truly eliminated in the earlier years, there should be progressive improvement in equipments that have been installed for longer periods. Yearly variations are apt to be irregular and confusing. Accordingly let us lump together, for example, all the operations for the years from 1933 to 1937 of just those relays installed in 1933 and then similarly for each succeeding year and so examine all the figures broken down in groups based on the year of installation.

Year Installed	Total Correct Breaker Operations	Total Incorrect Breaker Operations	Approximate Years in Service	Ratio Correct
1933	174	5	5	97 per cent
1934	170	17	4	91 per cent
1935	32	4	3	89 per cent

E. E. George (Tennessee Electric Power Company, Chattanooga): All relay engineers realize that there have been great improvements in carrier current protection in the last few years. The present paper is therefore very welcome at this time—particularly because it includes a schematic and circuit description of the latest practice. The detailed operating record given is also of interest to both manufacturers engineers and operating engineers.

Experience with a recent installation of carrier-current relay protection indicates that the total cost per terminal is now between $4,000 and $4,500 installed, depending upon the type of backup protection, if any. Taking the lower figure of $4,000 and applying the percentage of overheads commonly used by utilities for major equipment, one gets a total carrying and operating charge of something over $40 per terminal per month, which means that on the above basis the cost of carrier protection would pay for 20 to 30 miles of pilot wire between two terminals. This figure should be reduced slightly on account of the cost of the simpler pilot wire relays. However, it is obviously improper to apply the same percentage of depreciation, obsolescence, and maintenance to carrier-current equipment and relay equipment that is applied to power houses and transmission lines, so we may say that the figure derived above is too small. As another approach to the subject let us take the carrying and operating charges generally applied by communication companies to relay, switchboard and carrier equipment which works out to be about 30 per cent per annum—and this is admittedly insufficient on special equipment requiring particularly skilled maintenance. On such as basis this would give an operating and carrying charge of $100 per month per terminal, which would lease 25 miles of toll circuit per terminal or 50 miles of circuit between two terminals. Experiments are now being made to determine the utility of ground return or composite telegraph circuits (which takes a considerably lower rental for pilot wire purposes).

It is thus apparent that the length of the transmission circuit to be protected is a primary factor in determining the economic feasibility of carrier-current protection as compared with other methods. Among other factors are the availability of existing coupling equipment for carrier-current dispatching communication, the existence of trained personnel familiar with electronic maintenance, and the availability of high-grade communication channels between the power terminals, etc.

The industry owes much to the development of equipment and methods carried on by Mr. Sporn and his associates. While any endeavor to advance the art and science of electrical transmission may frequently subordinate economics during the development period, sooner or later economic considerations will determine how rapidly new developments are accepted into general practice. Any criticism of pilot wire relaying in a carrier relay paper invites such comparisons. Although the author of this discussion is just now making his first installation of carrier-current relay protection, his experience with pilot wire protection leads him to suggest that to the seven conclusions of Messrs. Sporn and Muller should be added the following:

8. Carrier-current relaying is now becoming the accepted standard on long transmission lines. On urban tie lines and short transmission lines (regardless of voltage) pilot-wire protection is more economical and is adequately reliable. On transmission circuits of intermediate length the decisions between the two types will depend upon many factors, such as existing dispatching communication practice, existing maintenance personnel, existing commercial communication channels, availability of new capital, and other considerations which are more largely economic than technical.

O. A. Browne (Western Massachusetts Companies, Turners Falls, Mass.): The paper presented by Mr. Sporn and Mr. Muller expresses a great deal of enthusiasm for the carrier-controlled relay which one can hardly appreciate unless one has had experience with it. Our system has had these relays in service at 26 line terminals since spring of 1933, and although some troubles have been encountered similar to those mentioned in the paper, they have all been fairly easily corrected and we are just as enthusiastic as the authors.

Our relays are all of the older four-cycle type used on line sections where either one or two tapped stations were involved. This, with other complications, made any type of overcurrent or distance type of relaying difficult to work out without cascading time and current settings to the point where lines were often burned off.

Since the installation of carrier equipment in four years we have had only one case of lines burned off during a lightning storm. Emergency line patrol and repair work on these lines during lightning storms has only averaged one case a year.

We found it desirable, as the authors did, to incorporate a time delay so that on the termination of a fault the receiver relay would not close the contacts blocking tripping until the ground and phase relays had a chance to open their contacts. We accomplished this by the installation of a capacitor in series with a resistor connected across the operating coil of the receiver relay. On the receipt of a carrier signal the capacitor is charged up. On termination of the signal the capacitor is discharged through the operating coil of the receiver relay, thus keeping it from resetting for four to five cycles. This seems to be a more positive method than the introduction of another relay with instantaneous opening and time delay closing, although it may not be applicable to the newer relays.

Reliability of tubes is borne out by our experience. In four years of operation, only one failure to block tripping could be attributed to a tube failure.

E. H. Bancker (General Electric Company, Schenectady, N. Y.): There is an intermediate stage in most developments after the principles have been outlined and the first installations made when people hesitate about adopting something new and look for the story of results secured by those who first dared to try it. The significance of this paper lies in the fact that it gives the results of several years' experience of an early user of many terminals of carrier relaying, a development that has been the subject of several previous papers, but all of which dealt with design features. Now we have the "proof of the pudding."

As a distinguished New Yorker was wont to say, "let's look at the record." First the adoption of carrier relaying was the only practical solution to certain operating problems. In other cases it was found to be the most economical solution. In still others it was the best, and even though something of lower cost might have served, the better performance expected from it was apparently thought worth its slightly higher cost. Thus, as was said of carrier relaying in its development stages, it has furnished the system designer and operator with a new tool of great utility. Secondly, it has come up to expectations in performance. As part III of the paper shows, the over-all accuracy on the comparison of correct and incorrect operations is not as good as might be desired although it compares favorably with other forms of high-speed relaying. The interesting and encouraging things are: (1) that the carrier system was called upon to function many times and the percentage failures were so small that the over-all performance was about as good as other relaying used for similar purposes; and (2) that every cause of a false operation was found and remedied so that the 1937 performance was better than could be expected of other forms of relaying. This indicates that while there may be growing pains, the adult is a healthy citizen.

Finally the carrier part of the equipment accounted for only half as many failures as were attributable to the relays. Certainly the relays cannot be said to be any more difficult to adjust and maintain than any others, and assuming what is probably true, that they were well maintained, it will be seen that the carrier part has an even better record of performance than relays. This means that the carrier equipment is even more dependable than relays, which should allay some of the doubts as to the reliability of a carrier pilot channel.

Naturally the results of experiences such as those cited in this paper are incorporated in the design as quickly as they are made known. Coupling-capacitor gaps are now enclosed in a housing at the base of the capacitor where they are protected against the weather. Line-trap capacitors are mica with no appreciable temperature error, and they are protected against damage from overvoltage by a distribution arrester having a characteristic that does protect even up to the highest traveling wave currents that may be expected.

In the modern schemes the contacts of the receiver relay are normally open and are mainatined so during an external fault so there is no race between them and the tripping relay after the fault has been cleared. Directional-relay contacts have been greatly improved by the addition of antibounce features. Moreover they normally close to stop carrier rather than open as in the authors' scheme where the additional tripping speed of a fraction of a cycle gained thereby was considered necessary. Directional relays themselves have much increased torque and speed with lower coil burdens as a result of the induction cylinder development.

The necessity for so many correct blocking operations has been greatly reduced by diminishing the area in which the occurrence of a fault causes an attempt to trip, through the use of distance relay elements.

With these many improvements, whose origin lay within actual experience such as is reported in this paper, results at least as good as those obtained in 1937 should be realized right from the start in any new installations.

A. F. Rose (American Telephone and Telegraph Company, New York, N. Y.): The first paragraph, in referring to the use of pilot wires for relaying, states: "Neither of the above schemes, however, has ever met with any great favor in the United States on account of the prohibitive cost of pilot-wire circuits, particularly on long lines, and because in the long run the scheme itself is no more reliable than the pilot wire. Experience has shown that the reliability of the latter is not quite at the 100 per cent level desired and mandatory for proper service." The authors apparently feel, therefore, that the carrier method is superior to the use of pilot wires. With respect to pilot wires leased from the telephone companies the following facts may be of interest. These facts relate both to relative costs and reliability.

With respect to costs, figures have been presented which indicate that the use of power-line carrier channels involves a first cost installed of about $4,000 more per terminal than the pilot-wire plan. The added annual expense for two terminals, including interest, insurance, administration, taxes, depreciation, and maintenance is probably not less than $2,500 (This figure is supposed to cover the allocated cost of all work, some of which might conceivably not add to "out of pocket" cost in an individual case but which would form part of an engineering comparison) which would seem to indicate that, in general, the use of leased channels would be economical up to 75 to 150 miles. The capital outlay and risk of obsolescence with the carrier scheme would thereby be avoided as would also the necessity of specially trained personnel for maintaining the equipment.

With regard to reliability, figures are presented in the latter part of the paper pertaining to the performance of a number of carrier systems over a period of several years. These figures show that out of about 2,000 occasions when called upon to transmit a signal, the carrier channels failed to function in 27 instances, only nine of which are, however, attributable to failure of the actual carrier channel. Converting the authors' figures to a percentage basis, which eliminates any need for consideration of the number of systems or years of service, we find that the carrier channels were out of service one-half per cent of the time, or putting it in another way, each circuit was on the average out of service about 1.5 days per year. Extensive summaries of failures on commercial telegraph channels, which should be representative of the type of channels which would be leased for pilot-wire relaying, indicate "out of service periods" of about an hour and a half per year. This is less than one-twentieth of the "out of service" time indicated for the power line carrier arrangement.

Philip Sporn and **C. A. Muller:** Referring to the statement of Mr. R. M. Smith that in the one-cycle system described by the authors the speed of clearing faults has been gained at the expense of reliability in blocking on external faults: Our opinion is that this is not true but, on the contrary, the scheme described is more reliable than the scheme employing circuit-closing contacts to stop transmission of carrier. It is evident that in the scheme described by the authors the employment of the auxiliary lockout relay prevents any false tripping from occurring on external faults due to quick reversals of power which occur on parallel lines and loop systems. On the other hand, in the scheme employing curcuit-closing contacts to stop transmission of carrier, the prevention of false tripping on external faults due to sudden power reversals is based on the premise that the directional relay contacts at one end of the line will open before the corresponding contacts at the other end of the line will close. It is the authors' opinion that under certain conditions the circuit-closing contacts may close before the circuit-opening contacts open, in which case false tripping would occur on external faults. The reason for this is that the relay whose function is to close its contacts on sudden reversal of power, has a much higher voltage applied to its potential coils than the directional relay whose function is to open its contacts. This is very apt to happen if the contact spacing of the directional relays is so adjusted as to obatin a maximum relay time of one cycle for the clearing of all types of internal faults.

In regard to Mr. Smith's comment of the auxiliary lockout relay introducing an undesirable time delay in clearing an internal fault which occurs immediately after an external fault, we wish to point out that it has been the authors' experience that this occurs very infrequently. However, when it does happen this extra time delay will amount to approximately three to four cycles, which is not considered very serious due to it occurring so seldom. Moreover, the employment of this auxiliary lockout relay gives out of step protection to the scheme without the addition of a complicated relay arrangement usually recommended for out-of-step protection on carrier current relay systems when such protection is desired.

The question of employing one set or two sets of fault detector relays, referred to by Mr. Smith, to prevent the possibility of incorrect tripping on external faults when the fault currents are near the minimum pickup value of the relays was thoroughly studied by the authors, and it was their conclusion that only one set of fault detector relays was necessary; the adoption of this obviously results in a simplified relay scheme. For phase protection it will be noted that the impedance-type fault detectors are employed. In case of an external fault, the fault detector at the line end where power flows into the bus bars has a lower voltage applied to its potential coil than the fault detector at the opposite end of the line has applied to its potential coil. Hence, this fault detector will have a lower current pickup than the fault detector at the other end of the line. However, this same fault detector starts transmission of carrier, blocking tripping action at both terminals of the line. Therefore, for phase-to-phase external faults no incorrect tripping should occur. For external ground faults, there is a possibility of incorrect tripping occurring when the ground currents are near pickup value of the ground fault detectors due to inaccuracies of current transformer ratios. However, the authors' experience up to the present time has not indicated an incorrect operation from this cause, thereby proving the infrequent occurrence of this condition. If future experience should show this to be serious, we expect to employ two ground fault detectors.

The authors believe the employment of a three-phase power directional relay is more satisfactory than the use of three single-phase power directional relays described by Mr. Smith. Our experience has been that a three-phase power directional relay is more reliable in its operation for phase-to-phase faults near the station bus bars. When applied to carrier-current relaying a much simpler relay arrangement is obtained than by the use of three single-phase power directional relays in conjunction with a ground directional relay. The type-*CBP* relay illustrated in the paper having only three phase elements is only applied when the minimum ground currents are far in excess of maximum load currents. In other words, it is only applied on the line section where ground-directional relays are not necessary. On line sections where ground-directional relays are necessary, the type-*CCP* three-phase directional relay is applied having three phase elements and a ground element operating on the same shaft. In this relay the ground element is made very sensitive and no difficulty is experienced with overcoming the torques produced by load currents. Furthermore, the employment of the type-*CCP* eliminates the use of a ground preference scheme, thereby simplifying the relay arrangement.

Finally, after carefully comparing the relay arrangement described by the authors with that described in the paper by Harder, Lenehan, and Goldsborough, referred to by Mr. Smith, the authors are of the opinion that the scheme they describe is a more simplified arrangement requiring less maintenance and having less likelihood of false operation. To an operating man the scheme described in the paper by Harder, Lenehan, and Goldsborough appears to be a Christmas tree setup with relays in profusion acting as the decorating medium.

Messrs. Rose and George both raise the question of the relative costs of carrier-current channels versus leased pilot wires from the telephone companies. The following figures may be of interest: The first cost for the system employing carrier-current channel is approximately $4,000 per terminal, which includes the cost of protective-relay equipment. Of this amount $2,400 represents the installation cost of carrier-current channel per terminal, and $1,600 represents the installation cost of the protective-relay equipment. The annual carrying charges, including interest, taxes, depreciation, and maintenance, for the carrier-current channel would be approximately $1,000 for two terminals. This represents a fixed and maintenance charge of over 20 per cent. Assuming a rental for leased pilot wires of $50 per mile per year for two conductors, then it is evident that the use of leased channels will be economical up to twenty miles instead of 75 to 150 miles as stated by Mr. Rose.

With regard to reliability of operation of carrier-current channels versus leased pilot wires, the following analysis may be of interest: The operating record of carrier-current relaying given in the paper covers 16 line sections which have been in service for an average time of 3.3 years. In other words, the operating experience given in the paper covers 53 line-section years. During this period only nine incorrect operations occurred due to the failure of the actual carrier channel. Extensive summaries of failures on commercial telegraph channels, which should be representative of the type of channel which would be leased for pilot-wire relaying, indicate "out of service periods" of about an hour and a half per line-section year. Then for the period covered by the operating experience in the paper, namely, 53 line-section years, the total outage period would amount to 79 hours. We believe that at least half of this outage period would occur during severe lightning and sleet storms just at the time that faults occur on transmission lines. The authors believe, and operating engineers in general will agree, that with the leased pilot-wire channel out of service 40 hours during severe lightning and sleet storms, that more than nine cases of trouble could be expected on the transmission system during that distress interval. There would of necessity, have to result more than nine incorrect relay operations chargeable to the leased pilot wire channel. It needs to be kept in mind, too, that all of the incorrect operations due to failure of the carrier channel occurred in the first two years of carrier-current experience, and that during the remaining two and a half years of carrier-current operation experience no incorrect operation occurred due to the failure of the carrier channel. Furthermore, these nine failures were all attributable to faulty design which has since been corrected, and no further failures from these sources are to be expected in the future. This has been abundantly demonstrated by the last two and a half years' operation, which was 100 per cent correct in so far as the carrier channel is concerned.

The authors are very gratified to find that the experience of Mr. Browne, both as regards to benefit obtained from carrier relaying and as to reliability of component parts of the equipment, has been the same as theirs.

Mr. Bancker's analyses of the cause of the original mild difficulties with carrier are interesting, and, the authors believe, to the point. They very definitely cannot quarrel with the conclusion reached by him, since they believe their experience definitely bears this out, and that results at least as good as those obtained on their system in 1937 can be realized in any new and modern carrier installation. The same thing holds true with regard to the discussion of Mr. Traver. The authors believe with him that the results that are being obtained with carrier today are something that neither they nor any other practicing relay engineer of a decade ago even dared to envision, and the results that are obtainable today with carrier are as close to perfect performance as there is a call for in a system aiming to give the very highest type of service. Carrier relaying very definitely has reached the point where its performance, given proper application engineering, can be predicted with the utmost certainty. That performance is in general so much of an improvement over anything that can be obtained by any other single relay scheme, that there does not appear to be any doubt that as its performance and functioning becomes better known, its use is bound to spread more and more widely.

A System Out of Step and Its Relay Requirements

Discussion of a paper by Leslie N. Crichton published on pages 1261–7 of volume 56, 1937, AIEE TRANSACTIONS (October 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the relays and reactors session of the winter convention, New York, N. Y., January 25, 1938.

E. H. Bancker (General Electric Company, Schenectady, N. Y.): Man's easiest way of learning seems to be through much repetition. Not many of us have frequent occasion to study loss of synchronism and yet it has an important effect upon the action of many types of relays. Therefore, although the information presented in this paper is not new, it is given in a new and easily understood manner, and as it is knowledge we relay engineers need, it bears repetition. Perhaps if we read or hear it enough times we may be able better to interpret records of peculiar relay action or to determine in advance what may be expected to happen to some of our relays when systems swing or lose synchronism.

A little work has already been done in determining how loss of synchronism affects relays, especially the distance type. This indicated that there was some danger of sectionalizing at several points between the machines out of step, thereby leaving areas without a source of supply. Several solutions have been proposed, most of them including means for preventing distance relay action under the circumstances and requiring an out-of-step relay to separate at the most convenient point.

As the author says, most out-of-step relays must wait for three or four slip cycles to differentiate completely between loss of synchronism and every other condition of operation. This should usually be satisfactory, but it may be of interest to know that it is possible, if necessary, to construct an out-of-step relay that will operate during the first slip cycle and for no other condition except loss of synchronism.

This paper will have served its purpose if it merely helps a few of us to get a better mental picture of the quantities existing when machines go out of step. The simple, direct analysis is a big help in acquiring an understanding of this complicated phenomenon.

H. R. Paxson (Philadelphia Electric Company, Philadelphia, Pa.): In Mr. Crichton's paper the graphical method of treatment of the conditions at different points on a system running out-of-step enables the rather complex current and voltage relationships to be readily visualized. This method of representation would have been extremely useful to us early in 1935 when the problem was forcibly presented to us by a large frequency converter pulling out of step and continuing to run out of synchronism until considerable damage to the machine resulted.

Previous to this occurrence we believed that induction-type overcurrent relays would furnish protection against a condition of this kind. This belief was based on the fact that our smaller frequency converters equipped with induction type overcurrent relays had been clearing successfully during out of step conditions. Since the induction relays in the case of the large frequency converter did not perform as expected on the occasion in question, an analysis of the problem was made for the purpose of developing suitable out-of-step protection. As the action of induction relays was first investigated a few words on them is appropriate at this time.

The reset time of an induction relay on zero current is constant for any given lever setting while its operating time is a function of the current so that on a varying current such as results from a synchronous machine running out of step, the relay contacts will swing back and forth but will not actually close until the current swings become great enough for the relay disk to travel farther forward than backward on each swing. The time taken by the relay is therefore the time required for the disk to oscillate back and forth until the summation of the differential amounts of travel on each swing equals the total travel.

For a given setting the inverse time-current characteristics of induction relays makes the number of poles which may be slipped before tripping a function of several variables which include the maximum value of the current surges as a percentage of the relay tap setting and the speed with which the disk resets on currents below the tap setting. On the basis of using relay settings determined necessarily by the maximum load and the need for selectivity with other relays, it was found that if the generating capacity was high compared to the rating of the frequency converter, induction disk relays will eventually trip on out-of-step conditions but if the generating capacity should be low they may not trip at all. As three pairs of poles had been established as the maximum number which the protective relays should allow the frequency converters in question to slip, induction relays were obviously inadequate for this application.

Fortunately an oscillograph record was obtained. This showed that two pairs of poles were slipped during the first second after clearing the fault which initiated the disturbance and that the number of pairs of poles slipped, increased to seven per second at the end of the ninth second where the record stopped. With this background a study of out-of-step relay protection was undertaken. A method of analysis somewhat different from that presented by Mr. Crichton was followed but substantially the same conclusions were reached with respect to the requirements which the relays should meet in order to distinguish an out-of-step condition from hunting, overload swings, and faults elsewhere on the system.

Several relay designs were considered but at the conclusion of the study the out-of-step protective scheme described toward the end of Mr. Crichton's paper was chosen and installed on both the 25-cycle single-phase generators and 60-cycle three-phase motors of two 30,000-kw and three 15,000-kw frequency converters. The out-of-step relays consist of a duodirectional watt element whose contacts are in series with an overcurrent element. The two elements working together operate a notching train of auxiliary relays so that three complete power reversals accompanied by overcurrent are required to pick up all the relays in the notching train and close the tripping circuit; a timing device automatically resets the notching relays.

The overcurrent elements were set to pick up on currents ten per cent above the continuous ratings of the machines and the timing device was adjusted to reset the notching train in five seconds on the basis that under out-of-step conditions more than three surges would always occur in this interval. These relays were installed in November 1936 and although a number of system disturbances have occurred their performance to date has been 100 per cent correct which tends to confirm the correctness of the principles that were developed.

F. C. Poage (Ebasco Services, Incorporated, New York, N. Y.): Rewriting the equation from the author's figure 1 (*F*)

$$I = \frac{E_G - E_M}{Z}$$

We have

$$I = \frac{E_G}{Z} - \frac{E_M}{Z}$$

Let us analyze the expression E_G/Z. E_G/Z represents a fictitious short-circuit current supplied by the generator which would flow in the system *if* the internal voltage of the *motor* were removed and replaced by a short circuit as in the author's figure 4.

Likewise, analyze the expression $-E_M/Z$. $-E_M/Z$ represents a fictitious short-circuit current supplied by the motor which would flow in the system *if* the internal voltage of the *generator* were removed and replaced by a short circuit.

Thus in this case the total current I, through a given portion of the circuit, is the sum of the two fictitious short-circuit currents whose directions are, one positive and the other negative with respect to an arbitrary positive reference direction.

The voltage between conductors (or between phase wire and neutral as in conventional polyphase calculations) at any given point in the system is the *sum* of the fictitious voltages existing at this point in the two cases, first: if the internal voltage of motor is eliminated and replaced by a short circuit, as in the author's figure 4, and second; if the internal voltage of the generator is eliminated and replaced by a short circuit.

So far this analysis has followed the standard, but not commonly used method of network analysis by the method of superposition.

The author's power system may thus be considered the summation of two systems, each having but a single generated voltage (internal voltage of motor or generator) with the other generated voltage removed and replaced by a short circuit. It is apparent that each of these two systems may operate at its own frequency, and in operating at its own frequency may be out of synchronism with the other system, producing pulsating or alternating variations in voltage, current, power, etc., at beat frequency (or slip) equal to the difference between the two machine frequencies.

The illustrations and discussions offered by the author clearly illustrate the results obtained when two such systems are combined in a step-by-step synthesis from the component systems. This method may be extended to calculate the currents and voltages existing in a complicated system having (*n*) generators or sources of internal voltage by building up from (n) systems, each of which has but a single generator or source of internal voltage with all other internal voltages removed and replaced by short circuits.

This analysis of the out of synchronism operation requires that voltages, currents, impedances, and power quantities be determined for each of the component systems operating at its own frequency. Each of such component systems may be analyzed by the standard methods of short-circuit analysis now well established.

It should be noted that the principal difference between the equations cited in this discussion and those used by the author is the exchange of polarity signs in the equations for voltage and current, which change should not be cause for confusion to the reader.

Temperature Limits for Short-Time Overloads for Oil-Insulated Neutral Grounding Reactors and Transformers

Discussion and author's closure of a paper by V. M. Montsinger published on pages 39–44 of this volume (January section), and presented for oral discussion at the relays and reactors session of the winter convention, New York, N. Y., January 25, 1938.

F. Von Voigtlander (Commonwealth and Southern Corporation, Jackson, Mich.) This paper suggests standards of time-temperature limits based on allowable insulation aging. The statement is made that devices with closed-type coils (that is, without oil ducts) could operate during a fault at somewhat higher temperatures than could devices with open-type coils (that is, with oil ducts), and the temperature limits for the closed-type coils are shown to be considerably higher than for the open-type coils, tables II and III. Under leif expectancy, however, it is shown that for a given set of conditions, ten operations per day are permissible with the open-type coils but only 1.3 operations per day are permissible for the closed type coils for the same conditions. The premises for the comparison of the performances of these two types of coils and their allowable temperatures do not seem clear.

From time to time it becomes necessary or desirable to use standard power of distribution transformers for grounding banks. The question then arises as to what is the permissible rating of the transformer whose rating under normal loads is known, when it is used on a one-minute of perhaps an even shorter basis as a ground bank. Could not a similar attack, as that developed in this paper, be used to determine the ratio say between the continuous rating and a short time rating of such transformers?

D. R. MacLeod (General Electric Company, Erie, Pa.): This paper by V. M. Montsinger is of value in determining the ratings of transformers for electrified railway systems. It is easy to show that two different load cycles having the same root-mean-square current will result in different temperatures. This paper and its predecessors show that the aging of transformer insulation is a function of the temperature and the time that the temperature exists.

The thermal characteristics of motors, rectifiers, converters, etc., differ widely from those of transformers and the temperature limitations of all these equipments differ. In selecting transformers for use in railway substations and on locomotives, multiple-unit cars, etc., the most economical design will only be secured by studying the load cycles on which the equipment operates. The ratings should be determined by calculating the temperature-time curves and interpreting these results in terms of the life of the equipment. This is of particular importance on rolling stock where space and weight is at a premium. Higher temperatures can be tolerated than on central station systems with the same aging because the load cycle is such that the transformers are idle or running cool a great part of the time.

This method of calculating aging units enables the engineer of a railroad to calculate the relation between the life he will obtain on an emergency load cycle with the life which he would obtain with a load cycle under normal conditions. He can evaluate the cost of reserve equipment in terms of reduced life on necessary equipment.

In short it enables the engineer to apply a transformer intelligently to fit the enconomic design of his particular system. The old method of determining ratings by the root-mean-square current failed entirely in this respect.

V. M. Montsinger: In connection with the point raised by Mr. Von Voigtlander, the higher temperatures for the closed type of coil were predicted on the fact that closed-type coils cannot be used to carry a load continuously as can open-type coils. It is, of course, true that for carrying current only during faults, open-type coils could attain higher temperature limits. For example, if 160 degrees is the safe limit for one minute for open-type coils, the one-minute temperature limit for closed-type coils to give the same aging should be approximately 135 degrees centigrade. This is covered in the paper. On the other hand, if 160 degrees centigrade is safe for closed-type coils, the temperature limit could be raised to approximately 190 degrees centigrade for open type coils. 160 degrees centigrade may be too conservative for open type coils but, as pointed out in the paper, we have no experience to justify increasing the temperature limit above 160 degrees centigrade for one minute.

I agree that it is possible to determine the ratio between the continuous rating and a short-time rating of a standard power or distribution transformer used as a grounding transformer. To determine the temperature rise of a power transformer when used as a grounding transformer, it will be necessary to obtain from the manufacturer the winding losses in terms of watts per pound or amperes per square inch. Any standard formula can be used to calculate the temperature rise.

I am glad to learn from Mr. MacLeod's discussion that he intends to make use of the method followed in the paper to obtain the ratings of electric locomotive transformers which carry heavy overloads for only a short time and with light loads or no load the remainder of the time.

While the method used in the paper was applied to a specific kind of service—faults on neutral grounding devices—there is no reason why it cannot be applied to any kind of power service.

It should be understood, however, that unless a transformer has been built to carry short-time excessive overloads, similar to locomotive transformers, there may be limitations other than the aging of the insulation. That is, the lead joints, bushings, load ratio control parts, etc., may cause trouble.

Characteristics of the New Station-Type Autovalve Lightning Arrester

Discussion and author's closure of a paper by W. G. Roman published on pages 819–22 of volume 56, 1937, AIEE TRANSACTIONS (July 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the lightning protection session of the winter convention, New York, N. Y., January 25, 1938.

K. B. McEachron (General Electric Company, Pittsfield, Mass): Mr. Roman's description of the use of the mica spacers and carborundum insert for the purpose of decreasing time lag is of interest to me since I experimented with both of these arrangements some years ago. I am sure it would be of interest if Mr. Roman could give an explanation of the apparent reduction in time lag when using the carborundum. Our tests seem to indicate that the effect was rather erratic and could not be depended upon to always give the expected reduction.

There has been considerable discussion concerning high currents through lightning arresters in recent years and I notice that Mr. Roman makes some mention of it in connection with the discharge capabilities of the new autovalve arrester. It seems to me that we have to be rather careful about our thinking and consequent practice with regard to high currents through arresters. Distribution arresters do not as a rule have the benefit of the shielding effects of overhead ground wires, and in many cases the insulation level is as high as the usual wood line designed transmission voltages, and in many cases will have as high or higher level than the steel-tower line. This indicates that the data already obtained for frequency of occurrence of currents of different magnitudes through distribution arresters may also be used for station arresters, at least until better data are available.

In general, it is safe to state that the difference between station arresters and line arresters is not altogether based upon the proposition that arresters in stations must carry more lightning discharge current than the so-called line type or distribution arresters. The choice must include factors such as protection level afforded, stability of performance, endurance for repetitive discharges and other factors of over-all reliability, but current-carrying capacity alone is not to be regarded as the criterion. As a matter of fact, when overhead ground wires are properly applied, close to the station at least, the current-carrying capacity of the arrester is not important, beyond certain limits which I will discuss.

The paper by McEachron and McMorris, presented also at this Convention, dealing with field measurements of discharge currents through distribution arresters, indicates in figure 1 that 95 per cent of the discharges recorded during 4,036 installation-years were less than 10,000 amperes and 99 per cent were less than 21,000 amperes.

Considering the fact that the wave shapes possible with lightning are not known, although it now appears from unpublished work that many shapes will be found, it seems wise from the point of view of getting the most reliable station protection to make all of the discharges conform to a certain maximum. Although we cannot control lightning itself, we can control the voltage which can reach the station by shielding the station, so that direct hits of unknown characteristics do not reach the apparatus. If waves of the 2,000 kv per microsecond, mentioned by Mr. Roman, are to be allowed in the station, then rates of rise of four kv per foot must be allowed for the distance between the arrester and the transformer, if the transformer itself were hit. Thus, with only 50 feet separation, 200 kv would have to be added to the arrester voltage. This simple calculation indicates how necessary it is to shield the station from at least the bad strokes, and this will of course shield the mild strokes also, if advantage is to be taken of the good characteristics of a lightning arrester.

It would seem that a proper policy is to pass the lightning discharge through a sieve, as it were, which is the effect of placing an effective ground-wire system over the station and the incoming circuit for at least 2,000 feet. Sufficient information is now available so that such a shielded area may be built so that one is certain that strokes to conductors within the area will be practically nil, even over a great many years. Such a construction places on the arrester a definite duty, instead of an indefinite and unknown duty, with the result that the protection afforded is predictable, and co-ordinated insulation may be designed to a definite protection level which may be demonstrated. In case the entire transmission line is not protected by overhead ground wires, a protector-tube installation can be made for most voltage and current ratings, so that flashover may be prevented when a wave of high magnitude meets the lower insulation level of the protected section.

With such an arrangement, the arrester and the overhead ground wire, together with the protector tubes if used, become a co-ordinated protection designed to function with certainty for the 220,000-ampere stroke as well as the 50,000- or 5,000-ampere discharge.

Furthermore, it seems to me, with as many multiple discharges as are now known to contact transmission lines, it does not appear to be wise to stress the arrester up to its limit when the protective shield over the station and adjacent lines will limit the duty on the arrester, maintaining greater factors of safety and increased reliability.

What I have said is not to be construed as an argument that arresters should not have a reasonable current-carrying capacity. They should, but, for station protection the arrester will do its job with greatest accuracy and precision if it is not called upon to discharge severe direct strokes of lightning. Furthermore, an arrester, which held the voltage down at its terminals to even normal line potential could not protect the apparatus if unlimited steepness of wave were permitted, unless the arrester were directly at the transformer terminals.

The best solution at present, therefore, for important installations at least, is to control both the magnitude and the maximum steepness of the incoming wave, by forcing it to travel through at least 2,000 feet of line conductor before reaching the arresters.

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): I wish to call attention to what appears to be an error in line *D* of figure 9*b*. This gives the 115,000-volt class impulse strength of the transformer major insulation as 700 kv. The maximum impulse applied to a 115-kv transformer is 630 kv or 5 per cent over the bushing flashover under standard atmospheric conditions. If line *D* represents the demonstrated transformer strength it should show 630 kv instead of 700 kv. Furthermore, according to my experience in obtaining volt-time curves, it should turn up for times less than approximately three microseconds. The one-microsecond value should be about 720 kv. If line *D* does not represent the test level it does not mean anything.

D. D. MacCarthy (General Electric Company, Pittsfield, Mass.): Mr. Roman's paper "Characteristics of the New Station-Type Autovalve Lightning Arrester" contains a very interesting description of the construction and performance of this arrester.

The multigap structure which normally insulates the arrester from the power line is called a "switch gap." The individual gaps in this structure are porcelain spaced, are without shunting resistors, and have carborundum inserts in the face of alternate electrodes for the purpose of improving the impulse ratio. It would be of interest to learn from Mr. Roman how these inserts act to reduce the impulse breakdown, if they are equally effective for all rates of rise of applied voltage, and if the effectiveness is reduced by the condensation of metal which may be boiled from the electrodes by severe surges such as he shows in figure 8.

It is believed that tests made by the writer to determine the effect of carborundum inserts on gap spark potential will be of interest. The spark potential was measured on five single gaps in series with an impulse voltage rising at 50 kv per microsecond.

The following results were obtained:

Test Number	Carborundum Inserts	Impulse Ratio			Number of Measurements
		Maximum	Minimum	Average	
1	In place	2.36	1.49	1.87	10
2	Removed	2.04	1.45	1.85	10

Previous to test 1, these gaps had been sparked over ten times with 60-cycle voltage, 20 times with 1,500-ampere impulses, and 43 times with impulse and power voltage simultaneously applied. It will be observed that on these tests the carborundum inserts had no beneficial effect and that the average impulse ratio is about 40 per cent higher than the average shown by Mr. Roman in figure 4.

The multigap structure used in the new autovalve arresters to interrupt the follow current is referred to as a "quench gap." A high 60-cycle breakdown has been obtained by shunting the individual gaps with resistances, and a low impulse breakdown is obtained by spacing the gap electrodes with mica washers. Since a high 60-cycle and low impulse breakdown are equally desirable in the switch gap, it would be interesting to learn why the same type of construction has not been used in both gaps. It is of interest to note that resistance shunts have been used in the quench gap in the new arrester. The benefit of resistance shunts has been realized for some time and this principle was applied to the Thyrite station arrester brought out in 1930. Unlike the new autovalve arrester, the Thyrite arresters have always used resistance in parallel with each individual gap in the arrester, which resulted in several benefits. The resistors control the distribution of the normally applied 60-cycle voltage so none of the individual gaps is overstressed. This permits each gap to carry its predetermined share of the applied voltage. It makes the voltage on each gap relatively independent of the effects of water or sleet on the outside of the arrester housing and also independent of the position of the arrester with respect to grounded structures. The resistance shunts also permit the design of an arrester which has a lower impulse breakdown than would otherwise be possible. It would seem that resistance shunts would be even more necessary in the switch gaps of the autovalve arrester than in the quench gap.

The valve element blocks in the *SV* arresters are cemented with a chlorinated wax. It would be of interest to know if Mr. Roman's tests agree with tests made by the writer and his associates showing that such waxes may generate explosive pressures in the event of an arrester failure.

Mr. Roman presents data in figures 6 and 7 showing that the voltage across the valve element during the discharge of impulse current depends upon the rate of rise of current as well as upon the current magnitude. Data are not given for the fastest rates of rise for low currents. Surges of this type will occur in service when the front of a steep surge is chopped by spark-over of line insulation resulting in low current amplitude but steep rate of current rise applied to the arrester. If data are available for low currents with very short fronts, it would be of value for Mr. Roman to extend the range of data of figure 7 to include currents as low as 1,500 amperes at rates of current rise of 10,000 and 20,000 amperes per microsecond. Based upon figure 7 it would seem the arrester voltage for low-current steep surges may exceed the voltage for much higher currents which have a slow rate of rise.

Figure 8 shows current and voltage oscillograms from tests on valve element blocks which were apparently made without the gap unit and without power voltage. The total time duration of the 53,000 and 79,000 ampere surges is about 12 microseconds to current zero. It is possible that surges of longer duration will impose a more severe thermal duty on the valve element even though the current magnitudes were relatively low. Mr. Roman states that "the current in the majority of the strokes is below 50,000 amperes." He also states that "we find that the new *SV* arrester will discharge the majority of direct strokes without damage to the arrester, and the arrester while discharging these high currents will offer a fair degree of protection to the connected equipment." To justify this last statement, Mr. Roman must have other data not presented in his paper. The necessary supporting facts would include data on the time to crest and duration of lightning strokes as well as on the current magnitude, the length of the circuit between the arrester and protected equipment so that the voltage drop on the circuit inductance could be evaluated, and performance data on the actual protection afforded by complete high voltage arresters taken when actually discharging typical lightning strokes with rated power voltage applied. Also subsequent test data should be obtained on the arrester to determine the effect of actual direct stroke currents upon arrester performance.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.): The quench-gap station-type lightning arrester described by Mr. Roman is interesting for several reasons. First, it would appear from figure 7 that the arrester has actually passed lightning currents in the order of 30,000 to 80,000 amperes, and I assume passed them successfully. Thus it would appear that we are not far remote from an arrester that can handle successfully direct stroke currents of the higher order of magnitude.

Second, rates of current rise as high as 20,000 amperes per microsecond are mentioned, as compared with our present AIEE standards for lightning arresters of 150 amperes per microsecond. While we have no knowledge that such high rates of current do exist in the field, it is gratifying to observe that they can be handled without undervoltage rise at the arrester when they do appear.

I would like to ask Mr. Roman if the characteristic performance of the arrester given in figures 4, 5, 6, and 7 is to be taken as the maximum, minimum, or average values, and what are the maximum deviations to be expected from the curve data.

In figure 9*b* I am unable to follow Mr. Roman's story on the protection of 115-kv service with the 121-kv arrester. The transformer is shown with an impulse strength of 700 kv and the lightning arrester with an *IR* drop of 530 kv, leaving 170 kv margin between the arrester and the transformer, which certainly seems reasonable. It should be noted, however, that the lightning-arrester terminal voltage is shown as a wave approximating a $1^1/_2$ x 40 full wave. Now the full-wave impulse test on a 115-kv transformer is 540 kv, not 700, which leaves a margin between the arrester and transformer of ten kv, i.e., less than two per cent, which is less than the tolerance of measuring either the test voltage on the transformer or on the arrester.

Although the author represents the major insulation of the transformer as being 700 kv, it is not conceivable that he proposes to protect the insulation to ground which may have a strength of 700 kv and not the turn to turn and coil to coil insulation which may be only 540 kv.

Again in figure 9*b*, curve *B* depicts the time lag curve of a $31^1/_2$-inch gap, called by the author a "co-ordinating" gap. The minimum impulse flashover of this gap is shown as 525 kv, and as mentioned above the full-wave transformer test is 540 kv, leaving a margin of less than three per cent. Further, this gap flashover of 525 kv is for a positive wave and if a negative impulse should inadvertently appear in service the voltage at the gap could rise to about 585 kv, i.e., about eight per cent above the full-wave test on the transformer.

I hope Mr. Roman can prove the suitability of the new quench-gap station-type lightning arrester without working to margins of two to three per cent between the lightning arrester characteristic and the tested strength of apparatus, and also without the use of an auxiliary air gap to back up the arrester.

W. G. Roman: Mr. Montsinger and Mr. Gross have questioned the data of figure 9*b*. Since this paper was prepared the transformer subcommittee of the AIEE committee on electrical machinery has authorized the use of kilovolts rather than gap spacing as a measure of transformer strength. Since co-ordinating gaps are no longer considered desirable, curve *B* of figure 9*b* can be eliminated and the demonstrated transformer substituted. This does not change the protection picture. In the paper it was pointed out that the arrester would not protect the $31^1/_2$-inch gap. The voltage across the arrester is approximately the same as the demonstrated transformer strength of 540 kv for long waves. In other words, a traveling wave of 5,000 kv results in an arrester drop approximately the same as the demonstrated transformer strength. As pointed out by Mr. Gross, we cannot expect to co-ordinate our protection with small differences between the arrester drop and the transformer strength. If practical, the station should be designed to prevent waves of this magnitude entering the station.

In answer to Mr. Gross's question, the curves of figures 5, 6, and 7 are average values and variations of plus or minus five to ten per cent can be expected. The data in figure 4 show the actual variation during a life test on four gap assemblies. These are representative gaps and indicate the variation to be expected.

Mr. MacCarthy's tests on gaps having silicon carbide inserts show higher impulse ratios than we have found. The tests were probably made under conditions which resulted in an unequal distribution of voltage across the gaps. Under these conditions, we have found the 60-cycle breakdown of the gap assembly will be reduced more than the impulse breakdown and the impulse ratio will, of course, be increased. In the autovalve arrester the gap tube and outer casing tend to distribute the voltage uniformly across the gap assembly.

In the higher voltage arresters, grading rings are also used for this purpose. Since the switch gap is concentrated at the top of the arrester where the highest gradients normally appear, this is not as difficult as it would be if the switch gap were distributed through the length of the arrester. We have found the silicon carbide inserts effective in obtaining a reduction in impulse ratio and their effectiveness does not seem to be reduced by either high surge current or power follow current. The chart of figure 4 shows the results of a life test using a surge of 4,000 amperes and power follow. There is no apparent change.

The resistance-shunted quench gap was specifically designed to have a high power follow interrupting ability and at the same time a low impulse ratio. But, since the low impulse ratio is apparently due to corona or a similar discharge at the point of contact between the electrode and mica gap spacer, we felt it desirable to insulate the quench gap from normal voltage. Also, by insulating the gap from line voltage the shunting resistance can be made low enough to divide the voltage equally across the quench gaps without the aid of external shields. Since there is no continuous loss due to leakage current to be dissipated, it is not necessary to ventilate the arrester.

A flashover of the autovalve blocks resulting in an arc through the chlorinated wax cementing the blocks in place can, of course, result in the generation of gas heat and can rupture the porcelain casing. However, it has been our experience that a power arc over the outside of the blocks, even without the wax, will usually result in bursting the porcelain casing.

Mr. MacCarthy asks if we have data for very high rates of rise and low crest currents. The points shown on the curves of figure 6 show the maximum rates of rise we were able to obtain at the particular crest currents shown. By using a more compact surge generator, or by placing a gap across the arrester to chop the wave on the rising front, these curves could be extended. By extrapolating the curves of figure 6 Mr. MacCarthy's point can be demonstrated. For example, the crest voltage across the blocks will be about the same for a 1,500-ampere surge rising at 7,500 amperes per microsecond as for a 10,000-ampere surge rising at 1,000 amperes per microsecond.

I believe the data presented in the paper, together with the available data on stroke currents, justify the statement that the arrester will discharge the majority of direct strokes without damage to itself and at the same time offer protection to connected equipment. Of course some of the more severe strokes may result in failure of the arrester, connected equipment, or both. The 5,000-kv surge entering a 115-kv station discussed above represents a border line case. In a paper describing arrester characteristics I do not see why we must consider inductive drops, ground resistance, etc. These are problems for the station designer and must be considered in applying the arrester, not in designing it.

I agree with Mr. McEachron that an arrester will do its job best if the station is so designed that the arrester will not be called on to discharge the more severe strokes. But I also believe it is well to know what the voltage across the arrester will be and its chance of surviving if it does discharge a severe stroke. The use of ground wires over the station and for some distance out over the lines is good practice. It is also important to place the arrester as close as possible to the equipment to be protected.

Some Engineering Features of Petersen Coils and Their Application

Discussion and author's closure of a paper by E. M. Hunter published on pages 11–18 of this volume (January section), and presented for oral discussion at the lightning protection section of the winter convention, New York, N. Y., January 25, 1938.

R. E. Hellmund: See discussion, page 304 of this volume (June section).

J. R. Eaton: See discussion, page 304 of this volume (June section).

J. R. North and **F. Von Voigtlander** (The Commonwealth and Southern Corporation, Jackson, Mich.): Mr. Hunter's paper gives a general résumé of some of the engineering features of Petersen coils and their application and it should be decidedly helpful to those concerned with the use of these devices.

There are many factors which must be carefully considered in determining the probable effectiveness of Petersen coils in a given application and, judging from our experience, these include:

1. Relative number of single-line-to-ground faults versus faults involving two line conductors.
2. Relative number of permanent ground faults versus transitory ground faults.
3. Magnitude of the in-phase component of fault current due to line resistance, insulator leakage, corona, etc.
4. System arrangement—radial, loop, multiple lines, relative location of lines.
5. Dynamic and transient over-voltages as may occur with faults at different locations, and the ability of the system insulation to withstand them.
6. Protective relay scheme and necessity for automatically clearing permanent ground faults.

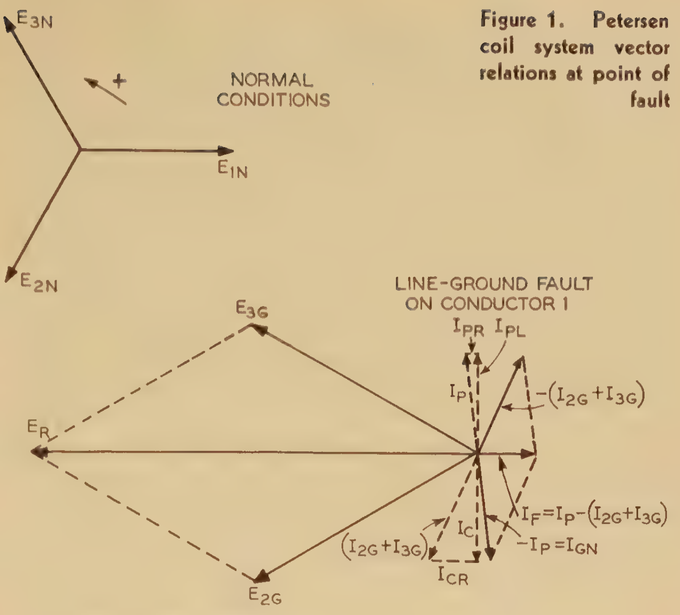


Figure 1. Petersen coil system vector relations at point of fault

E_{NG} = neutral-to-ground voltage
E_{1G}, E_{2G}, E_{3G} = line-to-ground voltages at fault (E_{1G} = 0)
E_R = residual voltage to ground = $E_{1G} + E_{2G} + E_{3G}$
I_C = quadrature component of charging current to ground from sound phases 2 and 3
I_{CR} = equivalent resistive component of current to ground due to conductor resistance, earth resistance, corona, etc.
$I_{2G} + I_{3G}$ = resultant line-to-ground current from phases 2 and 3
I_{PL} = inductive component of Petersen-coil current
I_{PR} = resistive component of Petersen-coil current
I_P = Petersen-coil current, ground to neutra
I_F = fault current

Petersen coils have been in operation for some years on our operating systems and we are of the opinion that they have a definite field of application in improving the performance reliability of transmission lines. However, this experience, combined with analytical studies and field tests, does not bear out some of the broad generalized statements made in Mr. Hunter's paper regarding the effectiveness of Petersen coils and it would appear that some of these statements should be qualified.

For example, the statement is made on page 11 of the TRANSACTIONS that the Petersen coil "*eliminates* transient overvoltages of the isolated-neutral system and the short circuits of the grounded-neutral system." We believe that the author here intends to convey the thought that the Petersen coil may eliminate the *effects* of the transient overvoltages. The coil automatically extinguishes the ground fault arcs initiated by the transient overvoltage (or other causes) and maintained by the dynamic overvoltage and so prevents these arcs from spreading to other phases to cause service interruptions. The thought should not be entertained that Petersen coils *eliminate* transient or dynamic overvoltages as this can be refuted by calculation, by test, and by operating experience. The use of Petersen coils may tend to limit the extremes of both the transient and dynamic overvoltages and a properly designed application may result in a considerable reduction of these overvoltages. Nevertheless, for certain conditions of system layout, fault locations, coil locations, etc., line-to-ground voltages well in excess of the normal line-to-line voltages may still be obtained during ground faults, even though the coil is in tune and successful arc extinction is obtained. Furthermore, the coils mitigate only the effects of transitory single-line-to-ground faults and have no effect on two-line-to-ground faults or line-to-line faults.

The statement is made on page 12 that "theoretically the leading charging current of the system is neutralized by the lagging inductive current from the coil, which results in zero current in the fault. In practice, this is approximated as closely as conditions will permit." Evaluation of the theory of Petersen coil operation will show, as is later discussed by Mr. Hunter, that only the quadrature components are neutralized and that during fault conditions the in-phase components of the charging current and of the Petersen-coil current are not neutralized, so *zero fault current* is never actually obtained, either theoretically or practically. This consideration of the in-phase components of the fault current is very important because the success or failure of the particular coil application may depend very largely upon this quantity.

Figure 1 of Mr. Hunter's paper is intended to illustrate the "vector relations of the components of current in a ground fault." This diagram is quite abbreviated and possibly might be misinterpreted. In illustrating current and voltage relationships by vector diagrams double subscript notations are always desirable. Figure 1 of this discussion shows the complete vector relations on a Petersen-coil system at the point of ground fault. The line-to-ground charging currents, the Petersen-coil current, and the unbalanced current in the fault are all shown in their proper relationship with respect to the system voltages from line to ground.

It will be noted that the current components consist of the following vector quantities:

$I_C = (I_{2g} + I_{3g}) - I_{corona}$
$I_P =$ inductance + resistive components of coil current
$I_F =$ vector resultant of I_C and I_P

It is mentioned on page 13 of Mr. Hunter's paper that test results may give charging currents as high as 50 per cent in excess of calculated values. This should be true only if certain important factors such as system layout, earth resistivity, overhead ground wires, and other factors affecting the zero-sequence impedance are not taken into account. When all these factors are considered, our studies on 44-kv and 138-kv systems have indicated that the charging current may generally be calculated with an accuracy of about ten per cent plus or minus and this has been substantiated by tests. The in-phase current components may also be predicted, but with somewhat less accuracy.

In the discussion of general applications on page 14, the author observes that theoretically one Petersen coil is sufficient to protect all parts of an entire system which are metallically interconnected. In an extensive system, the use of only one coil may permit such large in-phase components of fault current to exist that the effectiveness of the one coil would be considerably mitigated, whereas by the use of a number of smaller coils the charging current may be more fully compensated in the network branches.

Table I under "Remarks" should be corrected to read, "140 miles of line without ground wires," instead of "but 40 miles of line is without ground wire."

Referring to the "Summary" in Mr. Hunter's paper, item 3 may not be exactly clear as to the level of insulation referred to. With the overvoltage conditions which have been found by test to exist on Petersen-coil systems, it would seem that caution should be exercised in applying these coils to a system insulated only for what might be considered solidly grounded neutral operation with "full neutral displacement."

Item 4 should also be qualified, since the effectiveness of the Petersen coil depends upon a number of other factors such as: corona current, in-phase component due to unbalanced conditions, etc., as well as the size of the system and its circuit arrangement.

Mr. Hunter has called attention to the importance of the rate of rise of system recovery voltage at the fault location. This factor must be carefully considered in analyzing coil operation. Apparently, from the information available in oscillographic records of Petersen-coil systems, there is a relatively slow rate of rise of recovery voltage after the arc breaks and thus but little tendency for arc restriking. This rate of rise of recovery voltage is a governing factor in determining the maximum amount of fault current which may be successfully interrupted.

This discussion is intended to emphasize and to elaborate upon some of the statements made in this paper. It is not intended to in any way disparage the effectiveness or the desirability of Petersen coils when all the pertinent factors have been considered in their application to a power system. It is our purpose merely to point out the necessity for considering all the factors involved, particularly if the power system be of any extent.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): One of the discussers has apparently become so enthusiastic about the use of Petersen coils that he seems to think they might be used to advantage on underground cable systems operating at between 3 kv and 33 kv, especially since Petersen coils have been used on some underground systems in Europe. Almost all of the multiple-conductor cable purchased in this country has been obtained on the basis of neutral grounding, and the insulation thickness between the conductor and ground has been made substantially less than the insulation thickness between conductors. If the Petersen coil is used, then there may be a fault on one phase with the other phases operating with the full delta voltage between conductor and sheath for a considerable time. Such operation may be permissible for some cables, but it is certainly outside of the contractual arrangements and probably is not feasible for many installations from the standpoint of the strength of the insulation. In Europe there are comparatively more systems where the insulation thicknesses are the same between conductor and sheath as they are between conductors.

It is to be noted that the use of the Petersen coil on an underground cable system is not so beneficial as on an overhead system, because the fault does not clear itself. A faulted three-conductor cable usually could not be kept in operation very long, even with the help of the Petersen coil, since the residual unbalance current through the fault would very quickly burn the insulation of the other two phases and result in a two-phase or three-phase short circuit. The larger the system, the quicker the other phase would become involved so there is little likelihood of being able to keep a faulted three-conductor feeder in service until it is convenient to repair it, at least for our cable system.

The use of the coils on a system having both overhead and underground distribution such as our four-kv system does not seem to have any attraction from the standpoint of diminishing the effects of lightning. The overhead construction is such that flashovers limit the surges on the overhead system to 300 or 400 kv, which means that the resultant lightning impulses traveling into the cable are only a small fraction of the impulse strength of the cable insulation. When all kinds of troubles were taken into account, we found that only about ten per cent of our four-kv circuit interruptions might have been eliminated by the use of Petersen coils.

E. M. Hunter: Messrs. North and Von Voigtlander have summarized very nicely some of the factors which should be considered in estimating the probable improvement in service to be obtained by installing Petersen coils to an existing power system. They have very aptly pointed out that the success of a Petersen coil as a service protective device depends upon the faults being single phase to ground. On many systems at least 70 per cent of all the faults are single phase to ground On some systems it is possible to raise the degree of protection obtained by such supplementary aids as down wires on wood poles and low footing resistances which tend to keep the flashovers single phase.

On the other hand, service protection as such is not always the major issue. The reduction in maintenance on connected apparatus has more than justified the addition of Petersen coils to some systems which were formerly operated with the neutral isolated.

These discussers have stressed repeatedly the importance of the in-phase component of current in the fault. The Consumers Power Company 140-kv system which has Petersen coils has a relatively large in-phase component of current resulting from corona. It is probable that the magnitude of this component of current on this system is in excess of that to be expected on many systems. As far as I have been able to learn, of the more than 1,700 applications of Petersen coils in the world today, all have successfully functioned to quench transitory arcs to ground without the aid of any means to reduce the in-phase component of current. Fault tests have been made on a 33-kv Petersen-coil-equipped system with more than 1,300 miles of interconnected lines without excessive in-phase components of current being recorded. However, there undoubtedly is some maximum limit to the current that will successfully extinguish itself even with the relatively unstable arc that is obtained when the Petersen coil is properly tuned and where corona is present, the in-phase component of current warrants consideration.

The statement in my paper in connection with the accuracy of calculating system charging current is to the effect that measurements on 33-kv systems give currents that are as high as 50 per cent in excess of those calculated by the aid of Maxwell's coefficients. For those who wish to check this, a measured value of charging current in a ground fault on a 33-kv line with three-foot delta spacing and 4/0 conductor mounted on 30-foot poles was 0.22 amperes per mile. On high-voltage lines, there has been in general a closer agreement between the currents calculated by these coefficients and those obtained by test.

In connection with vector diagrams, the one in the paper has been drawn by viewing the system from the neutral where the Petersen coil is located to the point at fault while the discussers' is apparently drawn from a position at the fault looking into the system to the neutral where the Petersen coil is located. An examination of these two vector diagrams shows that in general they both correctly represent the neutralizing of the current in a ground fault. For example, on the discussers' diagram, although not shown, the system neutral is located one-third the way up the vector E_R from the point of fault. Drawing in a voltage vector from the neutral to phase one E_{1n}, on the discussers' diagram, will place the vector relations of system charging current and Petersen-coil current in the same relative positions that they occupy in the diagram in the paper.

The two diagrams differ in the presentation of the system residual voltage. The discussers' diagram shows the residual voltage E_R as three times the magnitude of the system line-to-neutral voltage E_{1n}. It is well known that such a voltage exists on a system only on the secondaries of those potential transformers which are connected to measure residual voltage. To show the residual voltage as three times the system line-to-neutral voltage and three times that actually existing on a system may lead to the erroneous conclusion that the application of a Petersen coil to a system will cause to be impressed upon connected apparatus three times the line-to-neutral voltage during each ground fault. Since this is decidedly not the case, this vector diagram with its residual voltage E_R should be shown with an explanation of what it actually represents.

Mr. J. R. Eaton has given a very interesting discussion of the recovery-voltage problem as it is associated with Petersen coils. It is to be hoped that he will extend this investigation and present a more detailed story of the correlation of his theory with actual tests.

Mr. Herman Halperin discusses the application of Petersen coils to cable systems. At the present time there are no Petersen coils on cable systems in the United States so that we have no operating experience from which the efficacy of this type of application can be judged. However, several installations of Petersen coils on cable systems have been made in England in the last year or so and since in the past English grounding practice has closely paralleled our own, it is of interest to learn of their experience with Petersen coils on cable systems. This has been given in a recent paper presented in London in December 1937, "Line Protection by Petersen Coils, With Special Reference to Conditions Prevailing in Great Britain," by H. Willott Taylor and P. F. Stritzl, which is to be published soon in the Institution of Electrical Engineers *Proceedings*. This paper reports in particular three separate single-phase faults on three-phase 11-kv cables, which remained single-phase for extended periods. In each case, the Petersen coil permitted the cables to be kept in service until repairs could be made. From these service reports, it appears logical to conclude that the application of the Petersen coil to a cable system warrants consideration.

Mr. R. E. Hellmund is of the opinion that the Petersen coil is not the best solution of a protective problem under *all* conditions, and I am fully in agreement with him on this. Duplication of circuits, overhead ground wires and counterpoises, expulsion protective tubes, and immediate reclosure of oil circuit breakers should all be considered with the Petersen coil and the one best suited for the application selected. Comments on these various other methods of protection will be found in the article "The Application of the Petersen Coil" by E. M. Hunter, in the *General Electric Review* for December 1936.

A New High-Speed Distance-Type Carrier-Pilot Relay System

Discussion and authors' closure of a paper by E. L. Harder, B. E. Lenehan, and S. L. Goldsborough published on pages 5–10 of this volume (January section), and presented for oral discussion at the relays and reactors session of the winter convention, New York, N. Y., January 25, 1938.

T. G. LeClair (Commonwealth Edison Company, Chicago, Ill.): Like all other improvements in the art, carrier relaying brings up additional and related problems which must be solved. Some of these problems which have arisen in connection with application of carrier relaying in Chicago may be of interest because they are likely to occur on other transmission systems.

Induced Currents

For the protection of two long overhead lines which parallel closely, a ground fault on one line introduces serious relaying problems due to induction. On the particular application in Chicago the current induced in the parallel line under maximum conditions will be greater than the fault current due to an actual fault on this line at minimum conditions.

In the case of two parallel lines supplied by a single bus and transformer, the induction is no problem, because the relative direction of the induced current and the transformer neutral current is used to obtain the directional effect. However, in the case of two lines frequently operated on separate bus sections supplied by separate transformers, the induced current flows through both the line and transformer neutral circuits and may trip the relay in error. This problem has been solved quite simply in one case by polarizing the directional relay on each line with the vector sum of the neutral currents in the transformers on both lines. In this case current in the faulted line and the net polarizing current (fault current minus induced current) are in the same direction on the faulted line and in opposite directions on the unfaulted line.

The problem is more complicated where the two lines have a parallel throughout most of their length, but have different destinations. For this case a solution which will work in some instances is the use of phase-to-ground voltage relays to prevent tripping on overcurrent unless the voltage on one phase has been reduced below a predetermined value. Also, negative-sequence current or voltage relays may be used. Another suggestion which has been made, and on which we would be interested in comments by the authors, is that of balancing out the zero-sequence current in phase-directional power relays. This can be accomplished by the installation of three three-to-one secondary current transformers in the neutral circuit of the secondaries of the main-circuit current transformers and con-

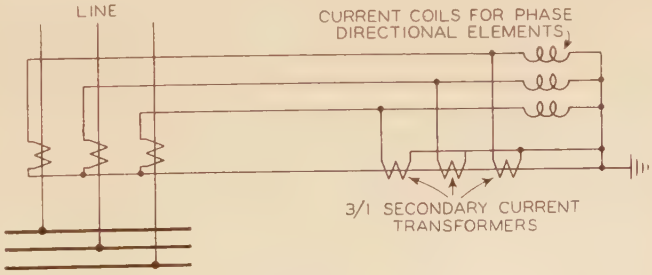

LINE
CURRENT COILS FOR PHASE DIRECTIONAL ELEMENTS
3/1 SECONDARY CURRENT TRANSFORMERS

Figure 1

necting each of these three-to-one current transformers to the current circuit of the phase-directional relays, as indicated in figure 1 of this discussion.

This application should be satisfactory where the overhead line has the normal number of transpositions so that the induced current will be distributed equally in the three phases. By the addition of these secondary current transformers, which add a third of the total ground current to the current from each main current transformer, the induced current will be balanced out and fail to appear in the relay. However, by actual fault on the line where the ground current appears in one phase only, this will not be the case and the relay will operate satisfactorily.

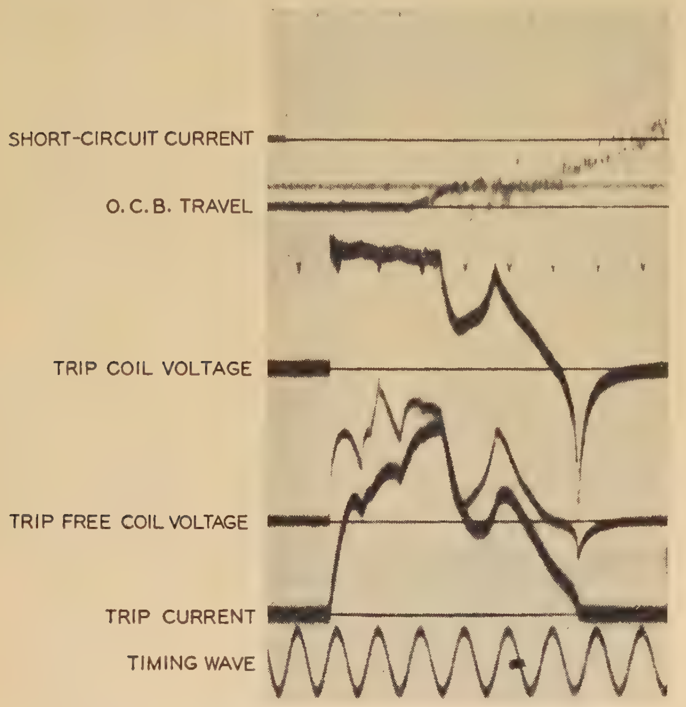


Figure 2. Performance of normal trip circuit, sustained fault

Application to Underground Cable

The application of carrier relaying with which we are concerned at the moment is that of a line having underground cable over six miles of its length and an overhead line for approximately 30 miles. It has been found that in some cases it is quite difficult to send the carrier frequency current through the underground cable. For the Chicago application we had a specially favorable opportunity to compare the transmission characteristics of an underground line with and without sheath-bonding transformers to reduce cable-sheath losses. We have two lines in parallel in the same underground duct section, each consisting of three single-conductor lead-covered cable. One of these lines is solidly bonded. The other has insulated joints in the cable sheaths, with the sheaths across the joints connected together through sheath-bonding transformers. It has been found quite difficult to transmit a carrier wave through the transmission line with the sheath-bonding transformers. On a simple test the solidly bonded line would transmit the carrier wave at practically any frequency between 50 kilocycles and 140 kilocycles with about the same attenuation as on an overhead line. The line with the sheath bonded transformers would transmit only a relatively few frequencies, and even at these frequencies the attenuation was much greater than that on the solidly bonded line.

It is evident from these preliminary tests that careful considerations should be given before an attempt is made to transmit carrier frequencies over underground transmission lines with an artificial impedance inserted in the cable sheath circuit. It is apparent that the circuit for the carrier wave is normally the conductor of the transmission line and that the return path is the sheath of the same cable instead of the general ground plane.

H. P. Sleeper (Public Service Electric and Gas Company, Newark, N. J.): This paper describes a system of carrier-pilot relay protection which compares the indications of instantaneous directional relays at the two ends of a transmission line and trips or blocks in accordance with this information which is communicated between terminals by means of a carrier-pilot channel which is normally not operative. It is now considered the up-to-date relay protection of this general type and relay systems operating on this principle have been in service for several years and are quite successful.

This scheme, which has been boiled down from about 15 years' experimentation with carrier-pilot relaying, has apparently arrived at a stable and fairly dependable stage. Having been until very recently, only an interested observer of this type of relaying, but having followed it on paper for many years, there is to my mind only a single fundamental fallacy in the present perfected scheme. I refer to the fact that when a fault occurs on a power system with this type of protection on all lines, it is necessary for the relay protection on all good lines, as well as all faulted lines, to operate correctly to secure selective relaying of the defective line. This is, of course, only an extension of any ordinary system of directional relays where direction alone locks out the operation of nearby breakers on good lines, but by virtue of the transmission of information of such elements in the carrier scheme to the far line ends, it requires the correct operation of considerably more elements than with standard relaying. Unfortunately, I have no solution for the problem, but there seems to be opportunity for further development work.

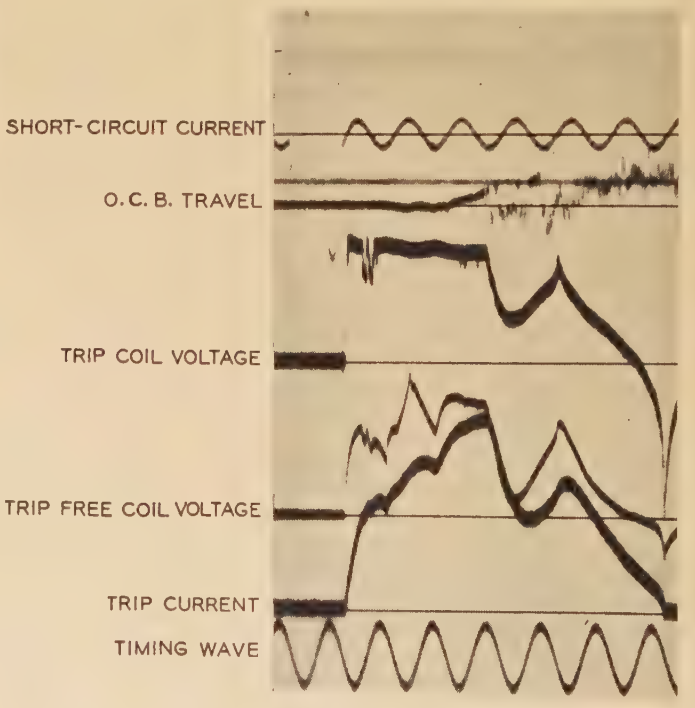


Figure 3. Performance of normal trip circuit, one-cycle fault

The authors of this paper recommend the use of several steps of distance relays to effect protection of a line unit; one to operate independently of the carrier system for a considerable number of faults on the line and back-up protection of the carrier; a second step to operate for end zone line faults and bus faults at the end of the protected section; and third step for general back-up protection for all faults beyond the line unit in question.

To the writer it would seem to constitute more efficient, dependable, and economic relaying to omit all back-up features and depend upon the carrier system alone for protection for all faults on the line in question. Similarly, the carrier protection on the next section of line would be likewise depended upon for its proper operation and no back-up relays provided in the carrier equipment. The busses would have their own differential relay protection which would be depended upon to clear its own faults, preferably, of course, with sectionalizing breakers to maintain service on the good part of the bus. Furthermore, the omission of all accurate distance-measuring elements on each line enables high-tension potential transformers to be omitted and only low-tension potentials used on the fault detector element, thereby effecting the saving of a considerable amount of money, at the same time obtaining more dependable operation of the directional elements by virtue of the impedance drop through the step-down power-transformer banks.

One problem which arises in connection with high-speed carrier relaying, or any type of high-speed relaying, and which has been recently solved by this writer in a manner believed to be novel, is that of preventing improper operation of such relays during transient short circuits, either phase-to-phase or -to-ground. There are many causes for such transient faults, which were very completely described in a paper entitled "Power System Faults to Ground" by Gilkeson, Jeanne, and Davenport, published in the April 1937 issue of Electrical Engineering. Such faults, which ordinarily last only a portion of a cycle, but may continue for as much as one cycle, will cause improper operation of circuit breakers on at least one end of a line with any system of modern high-speed relaying. Since expulsion tubes will nearly always cause such operation, it is absolutely necessary that the relays be capable of distinguishing between this and a legitimate fault which will be sustained, if not relayed out.

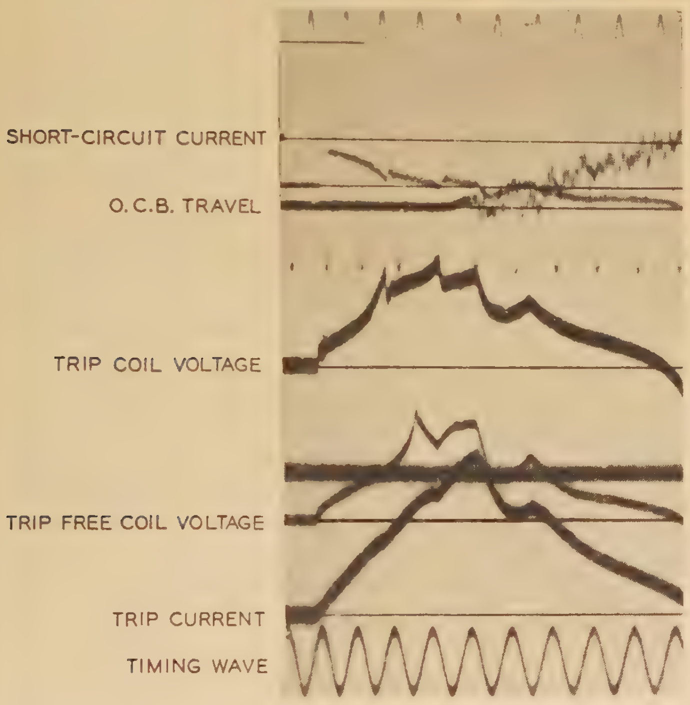


Figure 4. Performance of modified trip circuit, sustained fault

The solution worked out by the writer consists of the use of a reactor and condenser in the d-c trip circuit of the high-speed relays. Without such auxiliaries the reactance of this circuit is sufficiently low to allow the direct current to build up almost instantly when the relay closes contacts; and even though the contacts open a cycle later when the fault disappears, the arc will be maintained sufficiently long across the contacts to permit the high-speed breaker to open. The introduction of a properly proportioned additional reactance in series with the breaker trip coil and the application of a proper capacitance across the relay contacts prevents this in the following manner. When the d-c circuit is closed at the relay contacts, the trip coil current starts to build up, but very slowly because the L/R time constant of the d-c circuit has been considerably increased. Hence, the current to be broken on the relay contacts is much smaller than formerly after one cycle of time. However, this alone is not depended upon but the current is actually reduced to zero at the relay contacts by the creation of an oscillatory circuit caused by the exchange of energy between the condenser and the inductance of the trip coil circuit. Actually, the oscillogram shows that several oscillations occur, and of course, the direct current arc is broken at current zero.

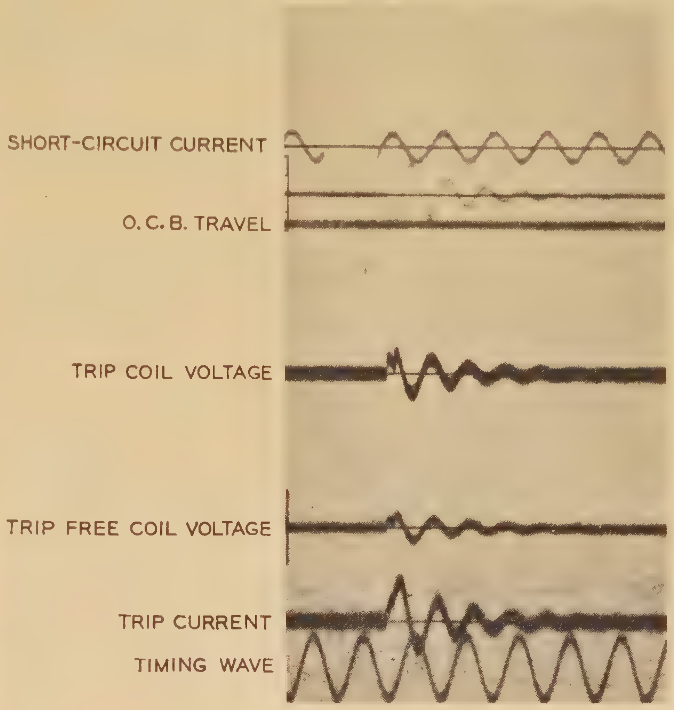


Figure 5. Performance of modified trip circuit, one-cycle fault

In actual operation the use of a two-microfarad condenser and a reactance of one henry, when used in the trip coil of a standard 37-kv circuit breaker, gave dependable operation so that a one-cycle fault was always removed without causing the circuit breaker to trip. Likewise, of course, a one- to two-cycle delay is introduced into the normal tripping operation of the breaker when a sustained fault occurs. The operation of the scheme is clearly shown in figures 2, 3, 4, and 5.

B. E. Lenehan and S. L. Goldsborough: Mr. LeClair's suggestion for removing the zero-sequence components from star-connected phase relays may have certain applications. The delta connection used in the paper removes the zero-sequence components. When system conditions are such that ground relays are not required, it is a suitable method of preventing induced current from tripping.

Sometimes, local conditions require certain limited power oscillations to be permitted without tripping. Star-connected phase relays will occasionally allow these oscillations to occur where otherwise out-of-step blocking would be required.

Where relays are required to operate on ground currents smaller than full-load current, separate ground relays are required. When maximum induced current is greater than minimum fault current, some other factor such as negative-sequence current line-to-neutral voltage or station-neutral current has to be introduced to properly select the operation desired. Each location has to be considered by itself to find the best additional factor to use.

We have carried on experiments in improving the transmission over an underground cable of the Public Service Corporation of New Jersey, which is equipped with sheath-bonding transformer. The joints were by-passed with four microfarad capacitors to simulate a continuous sheath at carrier frequency.

The transmission of the cable was greatly improved, approximately 30 decibels, in the ten-mile length. There are other factors to be considered, voltage induced in the sheath by switching surges and faults, being high enough to require protective gaps on the capacitors to prevent damage to capacitors or cable sheath insulators. A careful study will be required for each individual case to determine whether the power cable should be used for the carrier or a separate channel provided for it. As Mr. LeClair's tests have shown, underground construction does not necessarily bar the use of carrier-current relay protection.

The Thyratron Motor at the Logan Plant

Discussion and author's closure of a paper by A. H. Beiler published on pages 19–24 of this volume (January section), and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 25, 1938.

W. C. White (General Electric Company, Schenectady, N. Y.): The references to tube difficulties in this paper are of interest because they are typical of what occasionally occurs along wholly unpredictable lines when new devices are combined with new applications.

Structurally and except for slight differences in characteristics, the tubes used in this thyratron motor are identical to those used by the hundreds in thyratron control of seam welding during the past few years. In this welding-control application, the tubes have given satisfactory life and the nature of failure "cathode heater burned open," which is listed as the most common cause of failure in table I, has been absent. Careful analysis of this "cathode heater burned open" indicates that it is basically a mechanical breakage of a welded connection.

On the basis of all known factors, this thyratron-motor application represents less severe service on the tubes than that encountered in welding-control practice. Certainly the failure of welds, which commonly results from frequent intermittent operation and marked mechanical vibration, is absent in welding control. However, the fact remains that such failures did occur to an abnormal degree and, therefore, there must have been a special contributing factor in this thyratron-motor cubicle, which was probably a mechanical vibration of some unsuspected frequency. This might have originated either from the machinery in the vicinity or connected with the actual operation of the cubicle controls. A very simple and minor change in this small welded connection appears to have entirely eliminated this difficulty.

A paper on such unpredictable occurrences in other electrical fields, in addition to those that have been encountered from time to time in connection with tube applications, would undoubtedly prove interesting reading. Often first-class detective work is essential to get at the bottom of such unforseen combinations of factors.

Philip Sporn (American Gas and Electric Service Corporation, New York, N. Y.): The thyratron motor, like many other tube applications that have been developed in the past decade, again demonstrates the ease with which the solution of problems involving variation in flow of current for the obtaining of proper equipment characteristics, whether they be voltage, torque, speed, or related quantities, can be obtained by the use of electronic devices. The operating experience cited by Mr. Beiler clearly shows that everything expected in the way of performance at the time the application was first developed has been attained in practice. However, it also strikingly brings out the one serious weakness of electron tubes—their short life—due mainly to the lack of sufficient experience in the building of tubes, particularly those carrying fairly heavy current. I have on other occasions pointed out that until we get to the point where engineers begin using these tubes in quantity, we cannot expect major improvements either in cost reduction or in the qualities of reliability and life comparable to that attained with other more standard classes of equipment. The experience with the tubes on the motor again demonstrates this; further it shows that the causes of the difficulties can in most cases be determined and having been determined, remedies worked out. However, what there is lacking is the integration of sufficiently extensive experience under sufficiently varying conditions. Given that experience there is no reason why this one problem in tube applications cannot be solved.

A. H. Beiler: Mr. Sporn's point about additional experience being required with electronic control is well taken. It is natural for central station engineers to hesitate before applying such control to large power station auxiliaries, but once the ice is broken there should soon be available sufficient data to furnish clues for the detective work which Mr. White mentions.

Regarding Mr. White's other comments, it is possible that the shocks incident to removing and replacing cells in the cubicle may be partially responsible for the cathode-heater breakages, but I cannot help but feel that a contributing cause may be some at present obscure phenomenon associated with this particular application of thyratron tubes. Perhaps studies of the effects of commutation may shed additional light on this problem.

Mechanical vibration from an unsuspected frequency as suggested by Mr. White is a possibility. However, in view of the fact that the motor and its draft fan are the only rotating apparatus anywhere near the cubicle and that they run very smoothly this appears as a rather unlikely explanation. Within the next year there should be evidence indicating whether the new method of connecting the cathode heater has been really effective.

Transactions

Papers and Discussions Comprising Pages 295–358 of the 1938 Volume

Test and Operation of Petersen Coil on 100-Kv System of Public Service Company of Colorado

By W. D. HARDAWAY
MEMBER AIEE

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MEMBER AIEE

THE HISTORIC Shoshone-Denver transmission line of the Public Service Company of Colorado connects the Shoshone Hydro Plant with Denver and serves important loads in the Leadville and Idaho Springs districts in Colorado (figure 1). The line traverses mountainous country for most of its length, crosses the Continental Divide three times (figure 2), and is badly exposed to lightning. The design and construction work on the line was begun in 1906 and 1907, making this line the pioneer in its voltage class. Conductor spacing and tower clearances are very close in comparison with modern standards, and although progressive improvements have been made, the operating record of the line shows an average of 60 tripouts per year, of which 42 are chargeable to lightning.

Tapping this line at Leadville is a wood pole H-frame line supplying the Climax Molybdenum Company at Fremont Pass and the Empire Zinc Company at Gilman. Since this line is an integral part of the Shoshone-Denver system, operating records of both lines have been added to give the performance record shown in table VI, and the combined five-year average is 69.8 tripouts per year, of which 50.8 are chargeable to lightning.

The Shoshone-Denver line is a single-circuit line approximately 154 miles long with conductors horizontally arranged on steel towers. The conductors vary in size from 1/0 to 4/0 and are spaced 10 feet $4^1/_4$ inches to 10 feet 8 inches apart. A short section at the Denver end (2.22 miles) is on wood H-frames with 12-foot conductor spacing. The Leadville-Gilman tap, 30.5 miles long, is on wood H-frames with 13-foot conductor spacing. The average height of the conductors at the towers is approximately 40 feet. The line has no overhead ground wires with the exception of the 2.22 miles of H-frame line at the Denver end, which has one overhead ground wire.

Transpositions in both the Shoshone and Gilman lines are irregular, and were installed to accommodate occasional telephone parallels, rather than to balance charging current. For example, one conductor of the Shoshone line occupies the center position for 68 of the total 154 miles of line.

During recent years rapid growth of the mining load in the Leadville and Idaho Springs areas, served by these lines, has thoroughly justified steps toward improvement in service. The two obvious methods, overhead ground wires with effective tower grounding, or expulsion protective gaps, were investigated, but did not appear to apply, due to limitations imposed by the design of the existing towers. The additional structural loading of overhead ground wires appeared excessive, and the close tower clearances made successful application of expulsion gaps very difficult. The installation of a Petersen coil appeared to be a possible solution, and was particularly attractive as its cost estimated at considerably less than that of either ground wires or gaps.

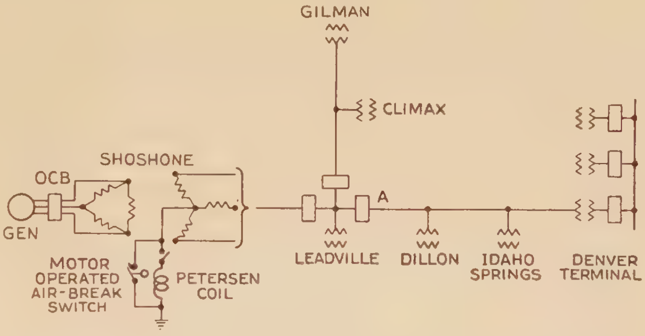

Figure 1. One-line diagram of system as normally connected

One apparent difficulty was that the line operates normally with appreciable corona loss, as the conductor is relatively small and the average elevation above sea level is 9,000 feet, with portions exceeding 13,000 feet (figure 2). Corona loss current, of course, is not compensated for by the coil. Also it was believed that the coil should be located at the center of the line to provide more accurate average tuning for faults at any point. The only neutral transformer point available was at Shoshone at the end of the line, so the cost of a grounding bank for intermediate location at Leadville or Dillon would have materially increased the cost of the project. Another

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Paper number 37-100, recommended by the AIEE committee on protective devices, and presented for oral discussion at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted October 6, 1937; made available for preprinting December 3, 1937.

W. D. Hardaway is superintendent, hydroelectrical production and transmission, Public Service Company of Colorado, Denver; W. W. Lewis is electrical engineer, central station department, General Electric Company, Schenectady, N. Y.

4. For all numbered references, see list at end of paper.

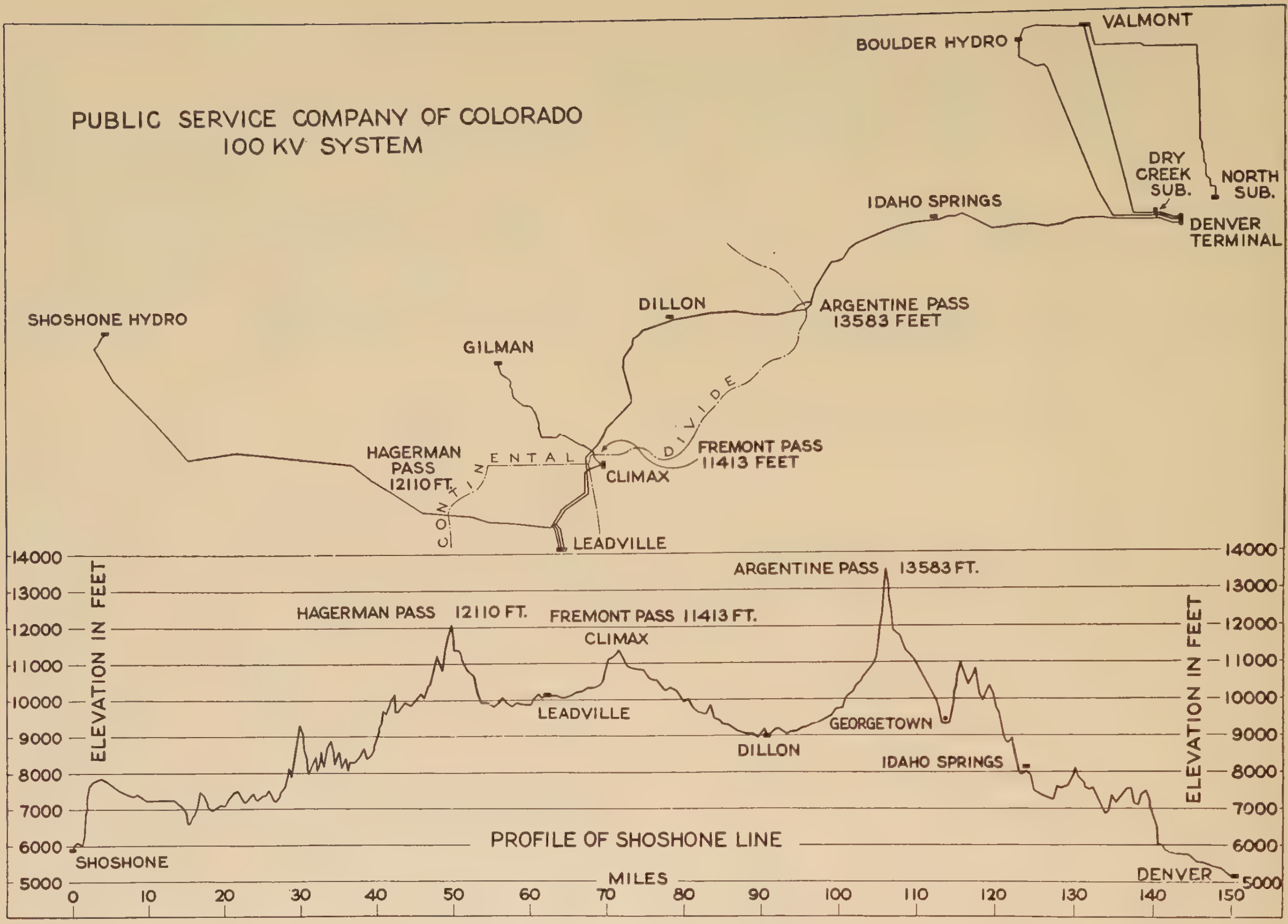


Figure 2. Map and profile of system

difficulty lay in the horizontal configuration of the line, close conductor spacing, low insulation levels, and high tower-footing resistance, all of which tended to produce multiple conductor lightning flashover, rather than single phase-to-ground faults which could be handled by the coil.

However, operating experience of the Consumers Power Company installation,[4] with heavier corona current than appeared probable on the Shoshone line, indicated that the corona problem was not particularly serious. Also, the Maine tests and Hunter's theoretical work,[8] indicated that a coil tuned for a fault at any point on a line would be in tune for faults at all other points on the line. This knowledge then permitted the selection of Shoshone for the coil location.

The problem of multiple-conductor flashovers still remained. Operating records were not very definite, but indicated that somewhat more than 50 per cent of the faults relayed out as phase-to-phase troubles. It appeared probable that some of these originated single phase-to-ground and developed into phase-to-phase faults before tripping. It appeared, therefore, that the coil would have a chance to extinguish some 50 per cent of the faults, and the installation appeared to be worth while on this basis. Furthermore, work was already under way on reconductoring and reinsulating portions of the line for mechanical reliability, which permitted increasing the normal suspension-string flashover distance from 30 inches to 38 inches, also a relatively inexpensive scheme of tower grounding or counterpoise was devised which would greatly reduce tower-footing resistances, and thereby the number of multiple-phase flashovers.

Under these conditions it appeared that a Petersen coil might initially quench up to 50 per cent of line flashovers, with the possibility of handling 75 per cent of the faults after the tower grounding and reinsulation work were completed. This was definitely economic, as no other scheme available approached this percentage of service improvement per dollar of investment.

Description of Petersen Coil

In the fall of 1936 some tests were made with the neutral isolated at Shoshone. A fault was placed on one conductor at Denver, each phase being grounded in turn, and the average of the three readings gave 123 amperes to ground at 95,000 volts line-to-line. With one conductor grounded at Leadville the charging current to ground was about 138 amperes at 95,000 volts line-to-line. Finally, a test was made on the Shoshone-Leadville section isolated from the remainder of the system. Extrapolating the results for the whole system gave 101 amperes charging current to ground at 95,000 volts line-to-line.

The Petersen coil as finally designed was rated 193 amperes for 10 minutes. The arrangement of the windings is such that there is practically a uniform voltage distribution throughout during transient conditions. The coil is insulated for the standard high potential and impulse tests for the 69-kv class (leg voltage of 115 kv). A shunting Thyrite resistor is installed inside the tank and designed to limit transient overvoltages to a safe value for the coil insulation.

Figure 3 shows schematically the arrangement of the coil and shunting Thyrite resistor. Ten taps are provided on a ratio adjuster for tuning and to take care of contemplated future extensions of the line, also disconnection of portions of the present line for maintenance.

Table I gives the approximate reactance values for the various taps, also the current rating for the three terminal tap connections. Based on an assumed value of 120 amperes for the present line from the preliminary tests previously mentioned, the coil will take care of a range of line from approximately 100 miles on the 855-ohm tap to 300 miles on the 285-ohm tap.

Figure 4 is an exterior view of the coil, showing the handwheel for adjusting the taps. Figure 5 is an interior view, showing the assembled core and coils and the shunting Thyrite resistor.

The coil was received in April 1937, and installed as shown in figure 1. It will be noted that the coil is installed with a stick-operated disconnect for isolation, and with a motor-operated air-break switch for by-passing the coil and solidly grounding the neutral. Although not so equipped initially, this motor-operated switch is now equipped with a timing relay which automatically closes the switch at the end of the pre-set time interval (approximately three minutes). The timer is controlled by a current relay in the Petersen coil lead, so that phase-to-ground faults not cleared by Petersen coil action are, at the end of three minutes, converted into single phase short circuits and the faulty section is relayed out.

During the period of April 21 to May 1 tuning and other tests were made on the system with the Petersen coil in circuit.

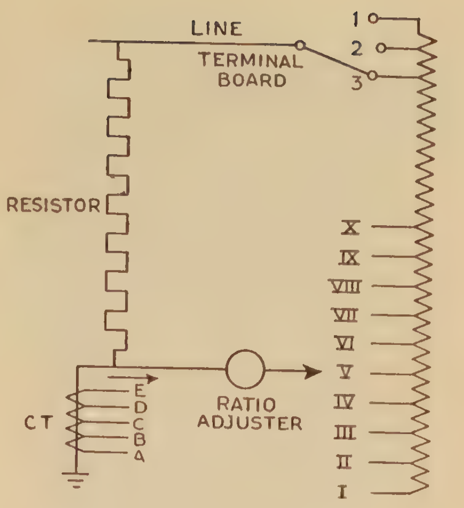
Tuning Tests

Figure 1 is a one-line diagram of the system as normally connected. All of the tests unless otherwise stated were made with this connection.

Table I. Petersen-Coil Taps

Tap Number	Terminal Tap I Ohms	Terminal Tap I Amperes	Terminal Tap II Ohms	Terminal Tap II Amperes	Terminal Tap III Ohms	Terminal Tap III Amperes
I	855	64.3	794	69.3	738	74.5
II	740	74.3	705	78.1	663	83.0
III	675	81.5	640	86.0	602	91.3
IV	620	88.8	587	93.7	547	100.5
V	570	96.5	530	103.8	485	113.3
VI	515	106.8	475	115.7	431	127.5
VII	468	117.5	425	129.4	382	144.0
VIII	440	125.0	395	139.2	347	158.5
IX	410	134.1	367	150.0	312	176.4
X	390	141.0	338	162.6	285	193.0

Figure 3. Schematic arrangement of coil, showing taps and shunting Thyrite resistor



The coil was adjusted or tuned with the system in two different ways: First, with no grounds on the conductors. In this case the ohms were varied and the amperes through the coil read on an ammeter. When the coil and system are in tune, the amperes are maximum. The amperes flow by virtue of a residual voltage caused by the unbalance in the capacitance of the three conductors to ground. The circuit consisting of the residual voltage, the coil reactance, and the capacity reactance of the system constitutes a series resonant circuit when in tune (figure 6*a*).

Second, with a ground on one conductor, the ohms of the coil are varied and the amperes read at the line fault. When the coil and system are in tune, the amperes are a minimum, and in fact would approach zero if there were no resistance, leakage, or corona loss. The circuit consisting of the line-to-neutral voltage, the fault, the Petersen-coil reactance, and the capacity reactance of the system constitute a shunt or a multiple resonant circuit when in tune (figure 6*b*).

Table II. Tuning Petersen Coil With No Grounds on Conductors

Tap	Ohms	Petersen Coil Amperes	Petersen Coil Volts	Product Ohms × Amperes
I	855	0.6	675	513
II	740	1.0	760	740
III	675	1.3	936	878
IV	620	1.92	1,250	1,196
V	570	3.2	1,870	1,823
VI	515	4.9	2,490	2,523
VII	468	3.15	1,380	1,475
VIII	440	2.25	980	990
IX	410	1.7	680	697
X	390	1.4	528	546

Petersen coil terminal on tap I.

Tuning Tests With No Grounds on Conductors

In this test the total system was in circuit with Petersen-coil tap I connected to the line. The ohms were varied through taps I to X, and the current in the coil was read on an ammeter.

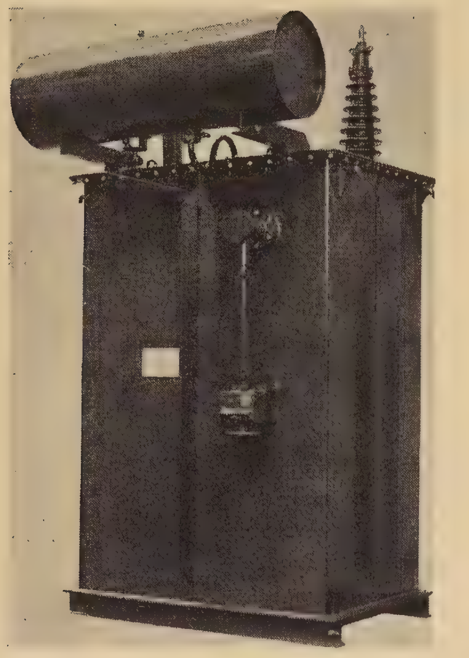


Figure 4. Exterior view of Petersen coil, showing hand wheel for adjusting taps

Table V. Insulator Flashover at Denver Terminal

Test Number	Insulator String	Petersen Coil Tap	Fault Duration (Cycles)	Amperes Fault Crest by Oscillograph	
16–1	5 Hewlett	VII	54	154 31	2d loop 30th cycle
16–2	7 Hewlett	VII	267*	260 31	1st loop 30th cycle
16–3	7 Hewlett	VII	48	142 31	2d loop 30th cycle
16–4	8 Hewlett	VII	57	148 31	2d loop 30th cycle
16–5	7 Hewlett	VI	56	222 31	1st loop 30th cycle
16–6	7 Hewlett	V	83	179 43	2d loop 30th cycle
16–7	7 Hewlett	VII	Fuse blew in oscillograph control circuit		
16–8	7 Hewlett	VII	840	74 37	2d loop 30th cycle
16–9	7 Hewlett	VI	57	265 31	1st loop 30th cycle
16–10	7 Hewlett	IX	322	 37	Off scale 30th cycle
16–11	7 Hewlett	IV	272	222 56	2d loop 30th cycle

* Opened by breaker.
Insulator string in test 16–4 dead end, in other tests suspension.
Petersen-coil terminal on tap I.

Table II and figure 7 give the results of the tuning tests with no grounds on conductors. In this test the maximum current was obtained on tap VI.

Tuning Tests With Ground on One Conductor

In these tests a ground was made on one conductor and the current in the fault read while the ohms of the Petersen coil were varied. Two sets of tests were made, one with a ground at Denver and one with a ground at Leadville.

Ground at Denver. In this test a ground was placed on the west phase at Denver by means of the transfer bus and an oil circuit breaker. The Petersen-coil ohms were varied and the current at the fault measured. The data are given in table III and plotted on figure 8.

Minimum current of about 22 amperes root mean square is obtained on tap VII, but the tuning is rather broad, taps VI and VIII giving only a slightly larger residual current.

Table III. Tuning Petersen Coil With One Conductor (West Phase) Grounded at Denver

Tap	Ohms	Petersen Coil Amperes	Fault Current at Denver (Root-Mean-Square Amperes)	Initial Fault Current From Oscillograph (Crest Amperes)	Product Ohms × Petersen Coil Amperes
IV	620	76	34.3	132	47,100
V	570	83	27.2	123	47,300
VI	515	90	23.1	126	46,350
VII	468	96	21.6	126	44,900
VIII	440	101	23.1	126	44,500
IX	410	107	29.0	83	43,900

Petersen-coil terminal on tap I.

Table IV. Tuning Petersen Coil With East Conductor on Gilman Tap Grounded at Leadville

Tap	Ohms	Petersen Coil Amperes	Fault Current (Amperes)	Ungrounded Phase Kilovolts at Denver*	Product Ohms × Petersen Coil Amperes
III	675	71	39	55.9–103.4	47,900
IV	620	75	33	56.0–102.5	46,500
V	570	83	27	56.0–102.1	47,300
VI	515	90	23		46,350
VII	468	98	22.1		46,300
VIII	440	105	24.1		46,200
IX	410	113	29.5	56.7– 99.4	46,350
X	390	120	36	56.5– 99.0	46,800

* First reading before conductor grounded and second after conductor grounded.
Petersen coil terminal on tap I.

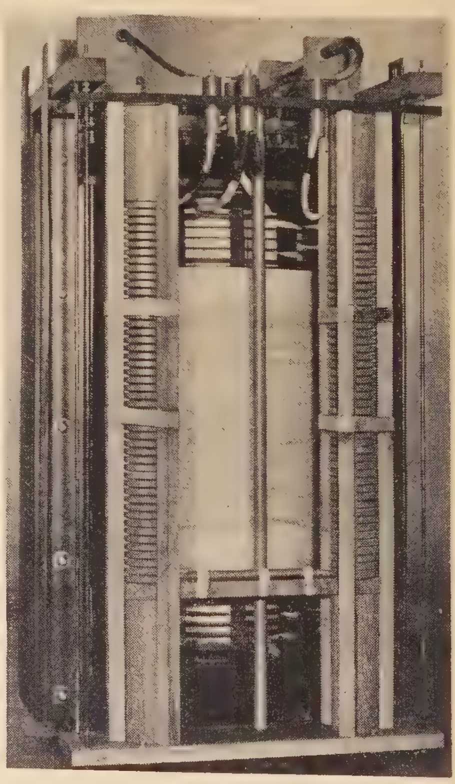
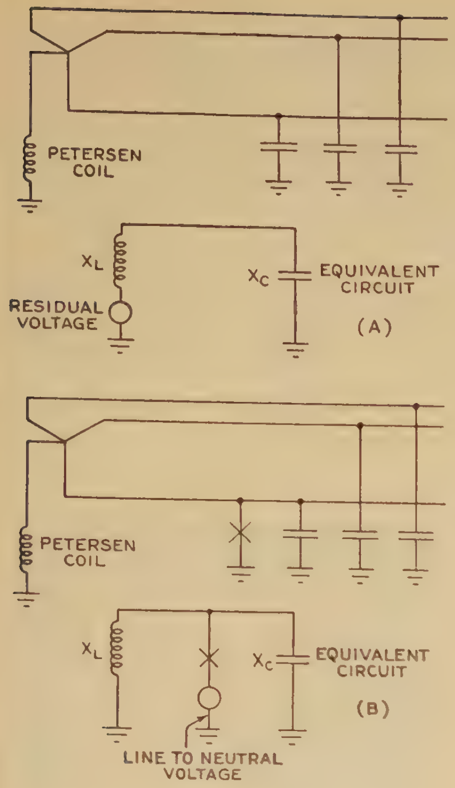


Figure 5. Interior view of Petersen coil, showing assembled core and coils and shunting Thyrite resistor



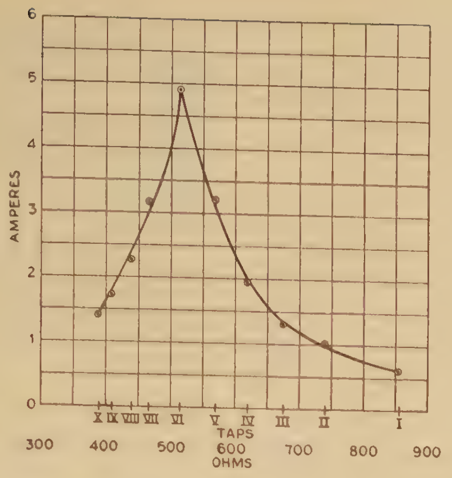


Figure 7. Tuning curve with no grounds on conductors

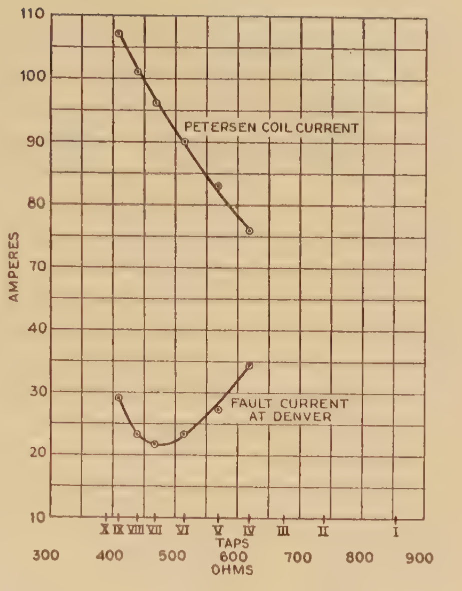


Figure 8. Tuning curve with ground on one conductor at Denver

Figure 6 (left). Equivalent circuits for tuning of Petersen coil

(a) No grounds on conductors
(b) Ground on one conductor

Conductor Grounded at Leadville. For this test the line connections were as shown in figure 9. The conductor was grounded at point *G*. The data are given in table IV and are plotted in curve form on figure 10. Here again the minimum current is obtained on tap VII and is about 22 amperes.

Arcing Tests

Several sets of arcing tests were made at Shoshone, Leadville, and Denver with the Petersen coil in service. Of these the most interesting were the tests with expulsion protective gaps at Leadville and the insulator flashover tests at Denver.

CONDUCTOR GROUNDED THROUGH EXPULSION PROTECTIVE GAPS

A series of arcing tests was made at Leadville using three 115-kv expulsion protective gaps of different bore.

The line connections were as shown in figure 9. The Leadville-Gilman line was connected to the main Leadville-Denver line at Robison switch rack. The Leadville-Gilman line was opened toward Leadville at Climax. This allowed the Climax and Gilman loads to be fed from the main line and gave a stub line from Leadville to Climax controlled through a breaker at Leadville for testing.

The tests were made at the first structure out of the Leadville substation on the stub line. This is a three-pole, wood dead-end structure.

The external gaps were set at approximately 13 inches and a fuse wire was placed across the external gap and through the tube of the expulsion protective gap. The Gilman line oil circuit breaker was then closed, thus throwing a fault on the east conductor at the point *G* through the expulsion protective gap.

Five tests were made on large-, medium-, and small-bore tubes with various settings of the Petersen-coil taps. In four tests the arc was extinguished in 0.5 cycle or less and in the remaining test in two cycles. In all cases the current interrupted was considerably under the minimum rating of the tube. In general the arc and the report were rather mild. Figure 11 is one of the oscillograms taken during these tests.

Table VI. Tripout and Flashover Record of the Shoshone-Denver Line for Five Years 1932–1936 Inclusive, and Portion of 1937

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Average number of tripouts, Shoshone-Denver line and Gilman tap, years 1932–1936, inclusive	1.8	0.6	2.6	2.0	6.4	7.6	26.8	15.4	3.0	1.4	1.2	1.0	69.8
Portion of above caused by lightning	0	0	0	0	4	7.0	24.4	14.0	1.2	0	0.2	0	50.8
Tripouts, 1937	1	2	2	1	10	8	8	2	0	1			
Petersen-coil operations, 1937					0*	7*	14	10	3	1			
Total flashovers, 1937	1	2	2	1	10*	15*	22	12	3	2			
Per cent of flashovers extinguished by Petersen-coil operation					0*	47*	64	83	100	50			

* Period of preliminary operation.

INSULATOR FLASHOVERS AT DENVER

At Denver terminal one five-unit suspension string, one seven-unit suspension string, and one eight-unit strain string were set up and arranged so that they could be thrown onto the transfer bus by means of an oil circuit breaker. Fuse wire was placed across the string to ground and this ground fault thrown on the bus by the breaker. All strings were composed of Hewlett disks.

Eleven tests were made, one on the five-unit suspension string, one on the eight-unit strain string, and the remainder on the seven-unit suspension string. This latter string has been adopted as standard for the sections of the Shoshone-Denver line which are being reconductored.

The tests on the five- and eight-unit strings were made with the Petersen coil on tap VII. The tests on the seven-unit string were made with various taps on the Petersen coil ranging from IV to IX. Table V gives the important data in regard to these tests.

Figure 12 shows the arc on the five-unit suspension string, with the Petersen coil on tap VII. The arc lasted 54 cycles. The exposure was for the full duration of the arc.

Figure 13 shows a one-fiftieth-second exposure of a typical arc over the seven-unit suspension string. In this particular test the Petersen coil was on tap V and the arc lasted 83 cycles.

During these tests there was practically no wind blowing. The small current in the arc would cause very little heating and consequent blowing and elongation of the arc. It is probable that these two circumstances together allowed the arc to persist from three-fourths of a second to 14 seconds in one case. Under lightning conditions there will usually be a wind, and the arc will probably snap out on an average in less time than in some of the tests.

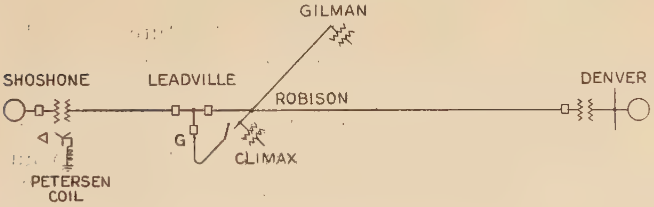


Figure 9. Line connections for arcing and tuning tests at Leadville

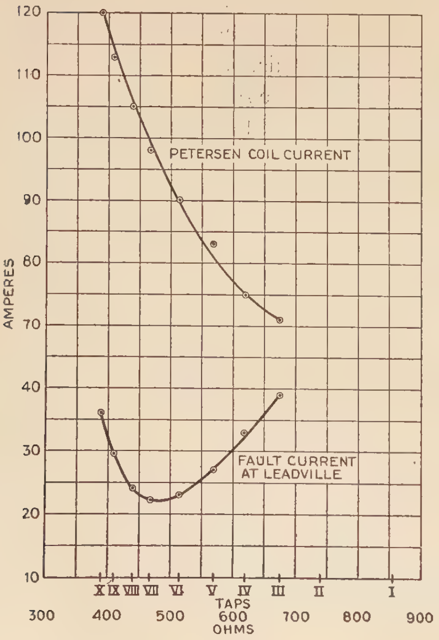


Figure 10. Tuning curve with ground on one conductor at Leadville

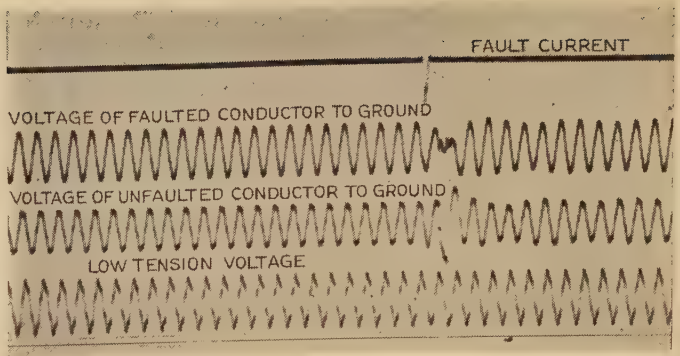


Figure 11. Oscillogram taken at Leadville during operation of expulsion protective gap with Petersen coil on tap I

Figure 12. Flashover of five-unit suspension string at Denver. Petersen coil on tap VII (test 16–1). Exposure for full duration of arc

An examination of the insulator units showed no damage to the porcelain or hardware as a result of these tests. There was no noticeable effect on the station lights nor any disturbance on the system with the exception of the ground-return telegraph circuit, which parallels the transmission line on the same right of way. This was disturbed in all of the arcing and tuning tests by induced voltage and circulating current. Figure 14 is a typical oscillogram taken during these tests.

Operating Experience

The coil was placed in service on May 1, 1937. From this date until July 1 may be considered as a period of preliminary operation. During this time unsuccessful attempts were made to work out relaying ideas at Leadville. It was hoped that an arrangement could be made which would select the faulty section of line and start a timer, which would disconnect the faulty section if the ground fault proved to be permanent, and was not cleared by Petersen-coil action. This idea proved not feasible with the equipment available, and was abandoned after some tests. Also, later operation has indicated that such a set-up, even if successful, would be of doubtful value, as the number of cases of trouble not cleared by coil action or normal phase relaying will probably be less than one per year.

An attempt was then made to arrange the ground relaying at Leadville so that it would be inoperative while the coil was in service but would be operative with the coil by-passed and the Shoshone neutral solidly grounded. This was readily successful on the Denver breaker at Leadville, but the relays on the Shoshone breakers there gave so many faulty operations that they are now kept blocked in normal operation and are manually made operative only when the Petersen coil is by-passed.

During the period of preliminary operation weak points on the system insulation were being discovered and eliminated. Two such cases involved flashovers on the Leadville transformers, which resulted in erratic relaying and interruptions.

By the first of July these difficulties were fairly well ironed out and the operation since then appears to be normal. It should be noted, however, that reconductoring, reinsulation, and tower-grounding work on the line has been progressing, and no doubt affects the operating results.

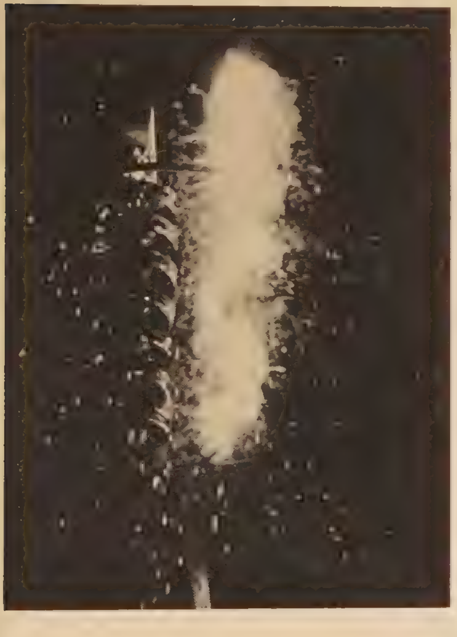


Figure 13. Flashover of seven-unit suspension string at Denver. Petersen coil on tap V (test 16–6). Exposure one-fiftieth second

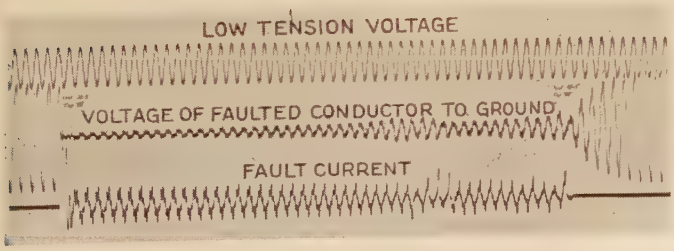


Figure 14. Oscillogram taken during flashover of seven-unit suspension string at Denver (test 16–3). Petersen coil on tap VII

Coil operation has been detected by a recording ammeter in the coil lead at Shoshone, by an automatic oscillograph at the Denver terminal, and by the effect of the communication circuit which closely parallels the transmission line.

For reasons which are not entirely clear, coil operation in service has been much faster than its performance in the staged tests, and it seems probable that some successful operations during the preliminary period passed unnoticed.

It has not been possible to keep the oscillograph on this duty continuously and some records have been missed. Oscillograms have been obtained of 21 operations. The duration of the arc ranged from 2 cycles to 216 cycles, and averaged 40 cycles.

Since July 1 all breaker operations, with one exception, have indicated as phase-to-phase or multiple phase-to-ground faults. The exception was a five-disk insulator-string failure within an indoor substation. This arc maintained for three minutes, then the Petersen coil was by-passed and the faulted section relayed out. All other single phase-to-ground arcs have been quenched by Petersen-coil action, without system disturbance.

The shock to the system at the time of coil operation is only that caused by the sudden increase in corona loss, two to three thousand kilowatts, and is negligible. However, the private telephone and telegraph circuit which is on the same right of way with the transmission line, becomes noisy and inoperative during the period of arcing.

None of the oscillograms obtained have recorded line-to-ground voltages in excess of normal line-to-line voltage.

Table VI gives a summary of the tripout data on the Shoshone-Denver and Leadville-Gilman lines for the years 1932 to 1936 inclusive; also the tripout and flashover record for 1937, during a portion of which the Petersen coil has been in operation. Between July 1 and November 1 the coil extinguished 28 out of 39 flashovers, or about 72 per cent, without circuit-breaker operation. The tripout in October was caused by a two-phase short circuit, no ground current being indicated. The fault was attributed to wet snow unloading and crossing the conductors at a transposition tower.

Conclusions

1. The Petersen coil and system were tuned by two different methods: (*a*) no grounds on conductors, varying coil ohms, and reading current through coil, and (*b*) ground on one conductor, varying coil ohms, and reading current at fault. Theoretically these two methods should give tuning on the same tap. Practically the second method sometimes requires lower ohms, because more coil current is required to balance the ground current, which is in excess of normal under this condition. The excess ground current is caused by increased capacitance due to corona, the corona current itself, and the harmonics in the charging current.

2. With one conductor grounded, tuning was on the same coil tap for a line ground at Denver and a line ground at Leadville. This confirms the conclusion reached after the Maine tuning tests, namely, that tuning would be the same for line ground at any point on the system.

3. The actual charging current at the fault was not measured during any of the tests. Assuming that it is approximately equal to the Petersen-coil current measured with a fault on one conductor, this will be about 97 amperes. This is about 1.65 times the calculated normal charging current of the system.

4. The Petersen-coil current with a ground at Denver and one at Leadville measured about the same (96 and 98 amperes respectively). Theoretically the current with ground at Denver should be considerably smaller on account of the increased line reactance. Voltage conditions at various parts of the system may have been sufficiently different during the two tests to equalize the Petersen-coil current.

5. The combination of Petersen coil and expulsion protective gap proved to be very fast and positive. In four out of five tests the duration of the fault did not exceed one-half cycle, although the current interrupted was only a fraction of the minimum rating of the tube. This combination may be valuable in locations where numerous line-to-line faults are experienced.

6. In the arcing tests over insulators, all arcs were successfully extinguished by the Petersen coil (one fault was removed by breaker at the end of four seconds). Time to extinguish the arc varied from 47 to 840 cycles. Air conditions were very quiet during some of the tests. The operating record indicates that during lightning conditions, there is usually sufficient wind to snap the arc out much quicker than in some of the tests. The observed average arcing time of 21 operations was 40 cycles.

7. The coil has been in service since May 1, 1937. In the first two months operation, trouble was experienced with faulty relay operation and breakdown of weak points in the system. In the following four months, the coil operated successfully to extinguish all single-phase-to-ground flashovers with one exception. The percentage of all flashovers extinguished by Petersen-coil operation in these four months averaged approximately 72 per cent.

References to American Literature on Petersen Coils

1. The Petersen Earth Coil, **R. N. Conwell and R. D. Evans.** AIEE, 1922.

2. The Neutral Grounding Reactor, **W. W. Lewis.** AIEE Transactions, volume 42, April 1923, pages 417–34.

3. Operating Performance of a Petersen Earth Coil, **J. M. Oliver and W. W. Eberhardt.** AIEE Transactions, volume 42, April 1923, pages 435–45, and volume 45, February 1926, pages 165–8.

4. Petersen Coil Tests on 140 Kv System, **J. R. North and J. R. Eaton.** AIEE Transactions, volume 53, 1934, pages 63–74.

5. The Petersen Coil, **W. W. Lewis.** *G. E. Review*, April 1935.

6. The Application of the Petersen Coil, **E. M. Hunter.** *G. E. Review*, December 1936.

7. Petersen Coil Installed on 100-Kv Colorado Line, **W. D. Hardaway.** *Electrical World*, September 11, 1937.

8. Some Engineering Features of Petersen Coils and Their Applications, **E. M. Hunter.** AIEE Transactions, volume 57, 1938, pages 11–18 (January section).

Discussion

H. M. Trueblood (Bell Telephone Laboratories, Inc., New York, N. Y.): Mr. Hardaway and Mr. Lewis state that none of the oscillograms have shown line-to-ground voltages in excess of normal line-to-line voltage. These are presumably the 21 oscillograms from the automatic oscillograph at Denver, which I assume is a magnetic oscillograph. The period of time covered by these observations is of course rather short. It is therefore interesting to recall[1] that in a series of 166 similar records extending over two years on one of the systems listed in table I of another paper,[2] the sound phase voltage to ground recorded by a magnetic oscillograph was less than normal line-to-line voltage in about 90 per cent of the cases.

There has been occasional skepticism regarding the reliability of the magnetic oscillograph for work of this sort, i.e., the recording of dynamic overvoltages at times of ground fault. Recent work of this nature in which the Joint Subcommittee on Development and Research has been participating indicates that such skepticism is hardly warranted. We have been finding that the magnetic oscillograph, with string vibrators tuned to about 3,000 cycles per second, appears to be quite a dependable piece of apparatus. It has been found to give good checks—within a few per cent on the average—with an automatic cathode-ray oscillograph, the tendency being apparently for the cathode-ray oscillograph to read slightly lower than the magnetic oscillograph.

It seems surprising that the observed coil current, as reported by Messrs. Hardaway and Lewis, should have been as much as 65 per cent in excess of the calculated normal charging current of the system, although this observed figure checks quite well with the empirical rule given[2] for medium voltage systems. Using 97 amperes as the charging current for the 187-mile system at 95 kv line voltage, the direct capacitance between one phase-wire and ground figures out to be about 0.0084 microfarad per mile. While data for an exact calculation of this capacitance from Maxwell's coefficients are not at hand, we estimate, from data for a somewhat similar system, that this figure of 0.0084, which presumably takes account of corona capacitance, is not more than 20 per cent above the theoretical value, without allowance for corona. I would be glad to learn the authors' views regarding this apparent discrepancy, which of course may have some simple explanation.

We infer, from a European publication, that an allowance of 10 per cent or so is considered about right in Europe (for a 100-kv system) for the various uncertain factors in capacitance calculations mentioned[2] exclusive of corona.

References

1. **Gilkeson and Jeanne,** AIEE Transactions, volume 53, 1934, pages 1301–09.

2. Some Engineering Features of Petersen Coils and Their Applications, **E. M. Hunter.** AIEE Transactions, volume 57, 1938, page 11 (January issue).

J. R. North and F. Von Voigtlander (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper presents in a very concise manner the results of the tests made in connection with the application of a Petersen coil to a 100-kv system. It is of particular interest to us in view of the similar tests and studies made in 1931 when considering the application of Petersen coils to a section of the Consumers Power Company's 140-kv isolated-neutral system. The Colorado and the Michigan Petersen-coil systems have somewhat similar characteristics.

The Colorado system which constitutes a total line mileage of about 185 miles is subject to very severe lightning exposures. It is located in a very high altitude, mountainous region where both the earth resistivity and the contact resistances are undoubtedly very high. The combination of these factors, coupled with the exposure to lightning storms of considerable intensity, probably contributes to the large number of trip-outs, averaging 38 trip-outs per year per 100 line miles. With the modernization of the line by adding more insulation, reconductoring with larger conductors and installing the counterpoise in addition to the Petersen coil, the number of trip-outs per year on the line should be reduced greatly.

The method of tuning the coil with and without faults on the line conductors is identical with the method followed during the Michigan tests, and corresponding conclusions are reached. Referring to our paper, "Petersen Coil Tests on 140 Kv System," presented at the winter convention in January 1934, it will be noted that the results of our tests definitely show that tuning of either one or both of the coils was not affected by the location of the fault nor by the particular conductor faulted. This fact was thus demonstrated long before the Maine tests (mentioned in conclusion number 2), although the complete mathematical proof of this fact may not have been worked out at that time.

Under "Operating Experience," the authors advised that bypassing the Petersen coil for the condition of a permanent fault, thereby operating the system essentially with a solidly grounded neutral during this period, was successful on the Denver breaker at Leadville, but not on the Shoshone breaker there; therefore, the relays on the Shoshone breaker at Leadville are kept blocked in normal operation and are manually made operative only when the Petersen coil is by-passed. Relaying by short-circuiting the Petersen coil during times of sustained faults has proved quite successful on the 140-kv system of the Consumers Power Company so that some question arises as to what the limitations of this method of operation were found to be in the Colorado installation. Was it due to the fact that with a ground fault on the Shoshone line section the relays at Leadville would only have charging current from the other sections to operate them?

It would be interesting to have explained the control for the coil by-passing switch and the relaying for sustained ground faults on the Colorado system, particularly for such faults between Leadville and Shoshone.

The statement is also made under the heading "Operating Experience" that none of the oscillograms obtained have recorded line voltages in excess of normal line-to-line voltage. In order to obtain maximum voltages on the system as described, with the Petersen coil located at Shoshone, a ground fault should be applied to one phase of the 100-kv system at that point, the maximum voltages appearing at the distant end of the line, at Denver. Test results under this condition of maximum voltage are not reported. Calculations which we have made and later substantiated by field tests show that line-to-ground voltages of as much as 130 per cent of normal line-to-line voltages cannot only be obtained, but can reasonably be expected in extensive systems, even though the system be equipped with a properly tuned saturating-core Petersen coil.

H. P. Sleeper (Public Service Electric and Gas Company, Newark, N. J.): Why is a Petersen coil like a French telephone? Because it required 20 years' use on the Continent to introduce it to the country. In retrospect this seems rather odd, particularly in view of the excellent operating results reported abroad. On the other hand it should not be forgotten that the Petersen coil was tested experimentally in this country as long ago as 1921 and found wanting as judged by United States standards of operation (see paper by Conwell and Evans, AIEE TRANSACTIONS, February 1922, volume 41). However, the present perfected device is a far cry from the experimental model tested by Conwell and Evans and does not have the drawback of sharp tuning characteristics and the predilection to series resonance of the early design. The iron core with its broad-top tuning curve permitting detuning of the system up to 25 per cent seems to have overcome the main theoretical difficulty. The saturation of the iron core and the presence of a surge suppressor across the windings prevent the propagation of high voltages throughout the system; this latter phenomenon being the most serious practical difficulty reported by the early investigators. But the device is not yet perfect and in spite of the glowing results reported by Hardaway and Lewis the time is not yet here when the operating engineer can prescribe the Petersen coil as an antidote for all ills that can befall the operation of a modern high-voltage power system. In this writer's opinion the reported result of 72 per cent correct Petersen coil operation seems optimistically high and it would seem that the sample of operation in this case is yet too small to give accurate data which can be used generally as a criterion of expected operating results over the wide range of operating conditions presented by the various voltages, types of pole and tower line construction, terrain grounding conditions, and many other possible variables that exist here as compared with similar practice abroad. The problem presented by the all-wood-pole line is an admittedly difficult hurdle for the Petersen coil and one which will unquestionably reduce the per cent of effective operation of this device. That is not to say that the Petersen coil should not be economically applicable to that type of system, but it will require the tempering of one's expectations of close to 100 per cent operation for this device.

However, while the Petersen coil may not be the ultimate solution, it does seem to the writer that it is at least the arrow that points the direction to a new phase of high-voltage transmission system operating psychology. The practice of relaying out a faulted member of a power system is a practice universally used in this country today and has been since such operation began. This is the doctor's method of cure by amputation. But surely it is more advanced psychology to cure the patient by palliative doses rather than by operation. The same psychology applies to the maintenance of service on power systems. Why relay out a defective unit if the fault can be removed without disconnecting it from service? This might be called the method of fault removal versus fault disconnection. The superiority of the former system over the latter is unquestionable. That it cannot at this time be attained 100 per cent in no wise reflects on the soundness of the new psychology. Neither is the method of fault disconnection 100 per cent effective, and frequently its efficiency is zero per cent from a maintenance of service standpoint. Furthermore, the ultimate economic effect of the new method will always exceed that of the old since theoretically no duplicate service is now required since no disconnections will occur. Of course this is a practical fallacy, but it is undeniable that a higher degree of service should be rendered by equal facilities, and an equal degree with fewer facilities. Obviously there is some point of economic balance to be worked out in the practical use of this theory.

I don't think that the Petersen coil is by any means the ultimate answer in the application of this new psychology of power system operation. Rather it is merely a sample, or introduction. It is inherently limited to the problem of one-phase-to-ground faults. This means that its theoretical efficiency is at once limited to some value between 25 to 90 per cent, depending upon many factors. Hence, the remaining 10 to 75 per cent of faults must still resort to the old method of treatment, namely, fault disconnection. But is it beyond the bounds of conception that phase-to-phase short circuits cannot be similarly treated? It is not, of course, because it is being done today with expulsion tubes. Hence, although it may not be economical, it is possible. It does not seem unreasonable to assume that it will be done in the not too distant future by this or some other means which is well within the limits of economical feasibility for more or less universal application.

Looking forward a bit, it seems probably that the Petersen coil as we now know it will be further perfected, or maybe it will be superseded by some brain child yet unborn. Likewise the phase-to-phase problem will probably be similarly solved economically by some perfection of existing devices or others not yet developed. But, whatever form they may take, it is the writer's belief that they will merely further justify the psychology of fault removal which has been demonstrated and practically effected by the Petersen coil. And regardless of what the form may be, or where perfected, it is hoped that it will not take operating engineers in this country another 20 years to acknowledge recognition.

J. G. Hemstreet (Consumers Power Company, Jackson, Mich.): The paper by Messrs. Hardaway and Lewis, dealing with the application and operating experience of a Petersen coil on the 100-kv system of the Public Service Company of Colorado, is of particular interest to us, since the conditions are quite similar to those on the Petersen coil section of the Consumers Power Company's 140-kv system. The 100-kv system in Colorado is not quite as long as the Consumers coil section, nor does it operate at as high a voltage. Also, there are two Petersen coils in operation on the 275-mile section in Michigan.

With the thought that the operating experience over a seven-year period with the two coils on the 140-kv system would be of interest and of value in this discussion, we are summarizing it in table I of this discussion.

It will be noted that during the six-year period when automatic oscillograph records were available, 94 per cent of the line-to-ground faults were cleared without breaker operation, whereas only four per cent of the short-circuit faults were cleared without breaker operation. Of the total faults, both during the six-year period and also throughout the total period of seven years, 72 per cent of all types of faults have been cleared without breaker operation and

Table I. Petersen Coil Operation on Consumers Power Company's System

	Six-Year Period, 1931 to 1936, Inclusive, With Automatic Oscillograph Number	Per Cent	Sept. 24, 1936, to Dec. 31, 1937 (Number)	Seven-Year Period Through 1937 Number	Per Cent
Number of faults					
Due to: Lightning	219	88	44	263	85
Sleet	3	1	1	4	1
Other causes	28	11	14	42	14
	250		59	309	
Line-to-ground faults	129				
Cleared without breaker operation	121	94			
Cleared with breaker operation	8	6			
Short circuits	45				
Cleared without breaker operation	2	4			
Cleared with breaker operation	43	96			
Not definitely determined	76				
Cleared without breaker operation	58	76			
Cleared with breaker operation	18	24			
Totals all types	250		59	309	
Cleared without breaker operation	181	72	42	223	72
Cleared with breaker operation	69	28	17	86	28

only 28 per cent required automatic sectionalizing of the faulted section.

It is interesting to see that this 72 per cent is the same as the experience in Colorado, as indicated in the paragraph immediately preceding the heading "Conclusions" of the paper by Messrs. Hardaway and Lewis.

We should also like to point out that during our tests, some of the arcs persisted for a considerable period. The actual operating experience with the Petersen coils has been somewhat better than that obtained during the field tests.

W. C. DuVall (University of Colorado, Boulder): In company with Professors Palmer and Eastom of the electrical engineering staff of the University of Colorado, I had the pleasure of witnessing the retuning of the Petersen coil of the Public Service Company of Colorado on the night of January 9, 1938.

If one witnessed this with the idea of seeing a spectacle, keen disappointment was in store; however, if it was viewed as an engineering achievement it was a keen delight. An arc that lasts for only two cycles is not much to see. I feel that enough has not been said about the slow recovery voltage of the faulted conductor. Oscillograms show that it takes about ten cycles for the voltage to reach normal. This gives ample time for the ionized air to dissipate and the insulation to recover to its normal value before normal voltage is reached. This slow recovery is inherent with the Petersen coil and seems to have its maximum time of recovery for the point of sharp tuning.

In the case of the Public Service Company tuning was found to be on tap number 6. Oscillograms taken between the faulted conductor and ground on taps above and below number 6 showed an oscillation, one beat was present. On taps number 5 and number 8 the voltage was found to pass through normal at about one cycle increasing and reaching a maximum overshoot at about three cycles, then decay and reach normal voltage in about ten cycles. This overshooting, or oscillation, is not present for sharp tuning. By using an automatic oscillograph and finding the tap that produces no beat is a third method of tuning and is probably the most accurate method. The reasons for this slow recovery voltage and the beat are rather complex. In returning to normal conditions the faulted conductor has its potential raised from a low value (zero in most cases) to phase voltage, conductor to ground. The clear conductors have their potential lowered from line voltage to ground, to phase voltage to ground. The charge on the faulted conductor is raised from zero to normal, the charge on the sound conductors lowered from that produced by line-to-line voltage to that produced by phase voltage.

If this automatic slow voltage recovery could be incorporated into into circuit breakers they could be redesigned more effectively. One more point: the *A. E. G. Progress*, April 1929, page 113, states that in Germany secondary cable networks of potentials as low as 3,000 volts have been successfully protected by the Petersen coil. Not to protect against surges produced by lightning necessarily but faults produced by accidental grounding.

The relative cost of Petersen coils versus relays and circuit breakers warrants some real investigation on the application to cable networks especially at voltages from 13,000 to 30,000. This is particularly apropos in the face of some recent serious cable failures.

R. E. Hellmund (Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.) [**Editor's Note:** This discussion covers also "Some Engineering Features of Petersen Coils and Their Application," E. M. Hunter, *EE, Jan. '38, Trans. p. 11–18*]: Various grounding means, particularly the Petersen coil, were the subject of extended discussion at the International Conference on Large Electrical High-Tension Systems in Paris last June. Unquestionably a rather strong case was made for the Petersen coil, and as a result even greater use of this coil may be expected in Europe in the future. Although I discussed some of the solutions common in this country, such as grounded neutral with high-speed relays and breakers, the use of deion gaps on the line, and the use of quickly reclosing breakers, it was obvious that the Petersen coil was favored by a large majority of those present at the meeting. However, regardless of this, subsequent inspection of apparatus and power systems did not convince me that the Petersen coil is the best solution under all conditions. For example, it is difficult for me to believe that the addition of Petersen coils to a well-sectionalized double line with high-speed relay systems and high-speed breakers would be justified economically. This would make it necessary to use transformers with a neutral fully insulated against ground, which, particularly in the case of tap-changing transformers, would lead to complicated and expensive designs. The European arrangements of this kind, while highly ingenious, did not impress me favorably as compared with the American transformer designs for solidly grounded neutral.

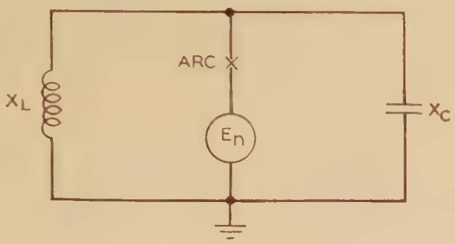
There was also a good deal of evidence that in some applications of Petersen coils the problem of lightning protection by arresters leads to considerable difficulty. It seems that during an arc to ground, which according to the papers presented today may last a great many cycles, overvoltages occur which are hard to handle by available designs of arresters. This has led to the practice of applying arresters with a greater margin wherever the insulating level of the system makes this possible. Frequently, however, the insulating level of European lines seems to be so low as to force close application of lightning arresters and consequent frequent damage to arresters. Nevertheless, there are a great many places, especially for medium voltages, where the Petersen coil can be applied to good advantage and its use should be given serious consideration in this country. As experience with the Petersen coil is accumulated for conditions prevailing here, a gradual increase in its use may be expected.

J. R. Eaton (graduate student, University of Wisconsin, Madison) [**Editor's Note:** This discussion covers also "Some Engineering Features of Petersen Coils and Their Application," E. M. Hunter, *EE, Jan. '38, Trans. p. 11–18*]: Mr. Hunter, in his paper, makes several statements regarding arc extinction on a Petersen-coil system, which on first examination appear contradictory. However, by a more careful analysis of the factors determining fundamental frequency recovery voltage across the arc, the statements are found to be in general quite correct. Refer to figure 1 which is figure 6 of the Lewis and Hardaway paper. Those authors have demonstrated that this circuit represents at least approximately the equivalent Petersen-coil system. It may be noted that this is a parallel resonant circuit energized by a generator connected to it through an arc. When properly tuned, the frequency of the resonant circuit is equal to that of the generator. Suppose the arc were to go out at current zero, as it always does at least until reignition occurs. The recovery voltage will be zero, because the voltage between the arc electrodes will be zero and will theoretically remain zero indefinitely. That is, the resonant circuit will continue to oscillate and the voltage of the condenser-inductance junction would be forever equal to, and in phase with, that of the line-to-neutral generator. Suppose next, that as in figure 2, resistance R_1 is inserted in series with X_L, and R_2 in parallel with X_C. When the arc goes out the resonant circuit will no longer oscillate indefinitely but will die down exponentially with time. The voltage across the electrodes will again be the vector sum of neutral and condenser voltages or

$$e = E_n \sin wt - [E_n \sin wt]\epsilon^{-at}$$

where a is dependent on the losses in the resonant circuit, and the rate of rise of recovery voltage will be

Figure 1



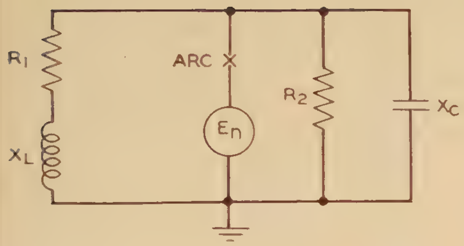


Figure 2

$$\frac{de}{dt} = E_n[w \cos wt - w\,\epsilon^{-at} \cos wt + a\epsilon^{-at} \sin wt]$$

At $t = 0$ this becomes

$$\frac{de}{dt} = a\,E_n \sin wt$$

Suppose again that the tuned circuit has a frequency slightly different $(w - b)$ from the generator frequency—that is, the Petersen-coil system is slightly out of tune. At the instant the arc goes out at current zero, the voltage appearing across the electrodes will be approximately

$$e = E_n \sin wt - [E_n \sin (w - b)\, t]\epsilon^{-at}$$

The recovery voltage is now dependent on both a and b.

Although apparently ignored in the past, a rather complete record of recovery voltage appears at the end of every oscillogram showing a ground fault on a Petersen-coil system. It may be observed that following the clearing of the arc, system conditions do not return to normal immediately, but change gradually as the transient in the oscillating current dies out. As the losses in the circuit determine the rate of decay of the transient, it is possible to calculate from the rate of decay alone, the ratio of the in-phase uncompensated current to the quadrature compensated current.

A study of recovery voltage on the basis of the above approach, shows quite strikingly that arc interruption is much more probable on a Petersen-coil system, whether in tune or not, than would be found on a simple LR or CR circuit having arc current of the same magnitude and phase position. Moreover, it shows that for best operation Petersen coils cannot be located at any point on the system but should be located near the major part of the system capacitance, rather than being tied through a long transmission line of high ohmic resistance. Any factor which tends to decrease the time constant of the oscillating system will result in higher rates of rise of recovery voltage and hence less probability of arc extinction.

W. D. Hardaway and **W. W. Lewis:** Doctor Trueblood expresses surprise that the observed Petersen-coil current was as much as 65 per cent in excess of the calculated normal charging current of the system. Measurements on five systems, varying in voltage from 33 to 140 kv, have shown the ratio of Petersen-coil current to calculated normal charging current to range from 1.75 to 2.15, with a fair average of about 1.9. The normal charging current is based on the capacitance to neutral, which is susceptible of fairly accurate calculation. The capacitance to ground is more difficult to calculate accurately, as it depends on the location of the ground plane, the presence of ground wires, the proximity of trees, the increase in apparent conductor diameter due to corona, etc. Tests on a 110-kv system consisting of one horizontal circuit with two overhead ground wires showed the average measured zero-sequence capacitance (capacitance of one conductor to ground when all three conductors are in multiple) to be 1.5 times the average calculated zero-sequence capacitance. The average measured zero-sequence capacitance of one vertical 110-kv circuit with one overhead ground wire was 1.2 times the average calculated zero-sequence capacitance. The calculated capacitance in this case was based on the actual geometrical relations at the towers, assuming the ground plane to be at the earth's surface, but with no allowance for trees, connected apparatus, or influence of corona on conductor diameter.

Messrs. North and Von Voigtlander asked for information as to the control for the Petersen coil by-passing switch and method of relaying for sustained ground faults, particularly between Leadville and Shoshone.

The Leadville relaying, before the Petersen-coil installation, included normal directional relaying for phase-to-phase faults, which is of course still operative. Phase-to-ground relaying was made selective between the Shoshone and Denver breakers by the magnitude of the fault current. That is, the residual or zero-phase-sequence current at Leadville for faults on the Denver side was much higher than for faults on the Shoshone side, and a satisfactory selectivity was obtained by blocking the Shoshone breaker trip when residual currents exceeded a definite value. When the current was below this value, a residual voltage relay was permitted to make a contact and trip the Shoshone breaker.

With the Petersen coil in service, it was not possible to find current values for the blocking relays which would be inoperative during the successful Petersen-coil operation, but which would still function when the coil was by-passed. The ground relaying on the Denver side has continued to function satisfactorily. The phase-to-phase relays will trip the Shoshone breaker under the condition of a single-phase-to-ground fault on the Shoshone side with the coil by-passed, although they are slower than is desirable.

The control of the coil by-passing switch is very simple. A current transformer in the Petersen-coil ground lead actuates an overcurrent relay, which starts a timer, set to make contact at the end of three minutes. The timer contact controls the closing circuit of a motor-operated air-break switch. Opening this switch is a manual operation. The performance of this air-break switch appears to be satisfactory, and the installation was much less expensive than an oil switch would have been.

As to the question in the last paragraph of the discussion concerning line voltages: As there are no high-tension breakers at Shoshone, we were not able to make tuning or grounding tests at that point. However, we made tuning tests at Leadville by throwing a ground on one conductor and during these tests we read the voltage at Denver on one of the ungrounded phases. These readings showed that the voltage jumped from approximately 56–57 kv to approximately 99–103 kv. In actual operation during the summer of 1937, the automatic oscillograph at Denver was in service with one vibrator on a potential transformer, which was connected between one high-tension conductor and ground. Oscillograms of 21 operations did not show any voltages in excess of normal line-to-line voltage, as mentioned in the paper.

Mr. Hemstreet gives some very interesting information in regard to the operation of the Petersen coils on the Consumers Power Company's system. In regard to his statement that the actual operating experience has been somewhat better as to duration of the arcs than obtained during staged tests, this checks with the Colorado experience. In the staged tests of May 1937 insulator strings were flashed over in 11 cases at Denver, the arcs continuing from 48 to 840 cycles. In a similar set of tests made at Denver in January of this year, consisting of ten insulator string flashovers, the arcs lasted from one to 688 cycles. In actual operation during the 1937 season in 21 cases the duration of the arc varied from two to 216 cycles with an average of 40 cycles. The increased persistence of the arc during staged tests is probably partly due to metallic particles and vapor from the fuse wire used to start the arc. On the other hand, during actual operation in lightning storms there is usually considerable wind, while in both sets of staged tests the air was quiet.

Tests of May 1, 1937

Test	Tap	Ohms	Maximum Crest Voltage of Grounded Conductor: Before Arc	After Arc
16–11	IV	620	100	123
16–6	V	570	100	104
16–9	VI	515	100	98
16–5	VI	515	100	100
16–8	VII	468	100	104
16–2	VII	468	100	104
16–1	VII	468	100	104
16–4	VII	468	100	104
16–3	VII	468	100	104
16–10	IX	410	100	119

Tests of January 9, 1938

Test	Tap	Ohms	Maximum Crest Voltage of Grounded Conductor: Before Arc	After Arc
1	IV	620	100	120
2	V	570	100	109
2*A*	V	570	100	113
3	VI	515	100	100
3*A*	VI	515	100	100
7	VI	515	100	100
4	VII	468	100	105
5	VIII	440	100	112
5*A*	VIII	440	100	113
6	IX	410	100	127

We are glad that Professor DuVall noticed and commented on the slow rate of recovery of the voltage at the faulted conductor and the overshooting when the coil is under- or over-tuned. The accompanying tables show the maximum crest voltage of the grounded conductor before and after the arc at the various taps, for the staged tests of May 1 and January 9.

Plotting the values of voltage after the arc as ordinates against ohms or taps as abscissas, we obtain curves similar to those of figures 8 and 9 of the paper, with the minimum points at tap VI. This undoubtedly indicates tap VI as the proper tap for tuning.

A possible explanation for the oscillation and overshooting of the voltage of the faulted conductor after the arc breaks is contained in a paper by one of the authors in the section headed "Arcing Tests" ("The Neutral Grounding Reactor," W. W. Lewis, AIEE TRANSACTIONS, volume 42, April 1923, pages 417–34, or AIEE *Lightning Reference Book*, 1937, pages 77–94).

Discharge Currents in Distribution Arresters—II

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TWO YEARS ago, the authors of this paper described to the AIEE a co-operative investigation by the Boston Edison Company, the Commonwealth Edison Company of Chicago, the Detroit Edison Company, the Georgia Power Company, and the General Electric Company, having as its object the determination of data relative to lightning discharge currents through distribution lightning arresters. At that time the results were based upon records obtained over a 13-month period from August 1934 to August 1935, inclusive. The object of this paper is to present the results from August 1934 to September 1937.

About 1,350 installations have been made for measuring lightning discharge currents, each installation consisting of two magnetic links supported by a wooden bracket, with the links spaced approximately three-quarters of an inch and two and one-eighth inches from the arrester ground lead in most cases. The use of two links not only permits a wider range of currents to be measured, but also indicates any reversal in the polarity of the discharge current.[1]

Table I. Distribution of Surge-Crest-Ammeter Installations

Operating Company	Line Voltage	Transformer Connection	Rural or Urban	Surge-Crest-Ammeter Installations		
				Present Number	Installation, Years to Date	Number of Records Obtained
Georgia Power Company	120–240		Rural	19	15	19
	2,300	Delta	Urban	37	70	72
	6,900	Delta	Rural	36	165	151
	11,500	Delta	Rural	81	300	192
	11,950	Gr. Y	Rural	97	305	155
Detroit Edison Company	4,800	Delta	Urban	78	119	11
	4,800	Delta	Rural	350	1,004	419
	24,000	Gr. Y	Urban	12	39	39
Commonwealth Edison Company	4,000	Gr. Y	Urban	324	1,002	169
	12,000	Gr. Y	Rural	20	39	16
	20,000		Rural	0	2	0
Boston Edison Company	4,000	Gr. Y	Urban	298	976	365
				1,352	4,036	1,608

As described in the authors' first paper on this subject,[2] the method of measurement used is accurate within ten per cent through a range from 500 amperes to 17,000 amperes for single unidirectional waves or for damped oscillations of the type used in making the laboratory calibration. Values down to 300 amperes and up to 25,000 amperes can be estimated.

When comparing data taken with magnetic links on different systems, or even on the same system, it is recognized that since it is impossible to be sure that links are changed after each stroke, there is bound to be a certain amount of superposition of results, the magnetic link recording the highest value if there has been no change in polarity. With different systems, the method of servicing the links was somewhat different, so that in some cases the effects of several storms may be superimposed. The effort has been to change the links after each storm in so far as this could be done economically.

Data concerning the four systems being studied are given in table I. The classification of circuits as urban or rural is entirely arbitrary. Those which have more than 12 customers per mile are classed as urban, all others as rural.

Results

To secure an over-all picture of the results, it is perhaps best first to examine all of the data from all of the companies, later breaking it down for a somewhat more detailed study.

MAGNITUDE OF CURRENT

Figure 1 shows the distribution of the discharges as to current magnitude, without respect to polarity or to the circuit involved. These results are based upon 1,608 records from 4,036 installation-years. These figures include 95 records and 145 installation-years in which current to ground was measured, but not through individual lightning arresters, as for instance on secondary neutral ground connections or in the common ground lead of three-phase arresters. Twelve records exceeding 25,000 amperes were obtained. These are included in the curve, but since their magnitude is not known, the curve is not plotted beyond 25,000 amperes.

This curve shows that 50 per cent of the discharge currents through arresters may be expected to be at least as great as 1,300 amperes, while only 1.2 per cent may be as large as 20,000 amperes. Although it is rather dangerous to extrapolate data of this sort, it would appear that an occasional record of 30,000 to 40,000 might be expected. A more accurate measure of the duty on an arrester is obtained if the results from the rural and urban locations are considered separately.

POLARITY OF CURRENT

In view of the work already done with respect to lightning currents through transmission line towers,[3]

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[1] For all numbered references, see list at end of paper.

considerable interest attaches itself to the polarity of the currents measured. Of the total of 1,608 records obtained, 1,011 were negative and 597 were positive. Based on the expectancy curves of figure 2, negative currents of 5,000 and 15,000 amperes may be expected 3.7 and 3.5 times as frequently as positive currents of the same magnitude. From the point of view of the performance of the arrester, either in protecting transformers or in keeping itself out of trouble, the polarity of the impulse is of no consequence. However, it appears to be quite firmly established that direct strokes of lightning reaching transmission line towers[3] are about 95 per cent negative, although the polarity of strokes to open country is believed to be more evenly divided between positive and negative. There is laboratory evidence that the so-called cone of protection around a grounded point is greater when the point is positive than when negative. If this can be applied to natural lightning, negative cloud discharges to positive transmission lines would concentrate on the lines a much higher percentage of the total discharges than if the polarities were reversed. As the line becomes lower in height, the positive and negative discharges would approach each other in frequency of occurrence, assuming equal numbers of positive and negative discharges over the terrain involved. This is of course somewhat of a speculation, but does seem to have some foundation.

Comparison of Urban and Rural Results

In figure 3 are plotted expectancy curves for all urban and all rural arrester discharge currents. These results indicate that the rural arrester will be called upon to discharge a current of 500 amperes about twice as often as an urban arrester; at 15,000 amperes the rural arrester must discharge about nine times as often as the urban arrester.

From the standpoint of duty on the arrester, these results indicate that one rural arrester out of 50 installed will discharge a current of 15,000 amperes or more each year, while but one out of 450 urban arresters will be called upon to discharge a current of 15,000 amperes or more in any one year.

The number of records per installation-year for all arrester installations is 0.39, while the corresponding values for rural and urban installations are 0.51 and 0.28. On the basis of equal numbers of installation-years in rural and urban locations, 81 per cent more records of all current magnitudes are obtained on rural circuits. These values are based upon the average of the results for a large number of measuring locations. The severity at certain installations with greater than average exposure may be considerably greater.

Discharge Currents Through Urban Neutral and Phase Arresters

Since the magnetic-link installations in Boston are equally divided between six-kv phase arresters and three-kv or six-kv neutral arresters, a direct comparison between neutral and phase arresters may be obtained from the Boston data. These circuits were originally installed as 2,400/4,160-volt three-phase four-wire ungrounded neutral circuits, but the neutrals have since been grounded without making any changes in the arresters used. One hundred sixty-six phase-arrester current records and 189 neutral-arrester records were obtained. The number of installation-years in each case is 488, giving 0.34 records per installation-year for the phase arresters and 0.39 for the neutral arresters. For all practical purposes, it can be stated that the number of records is the same;

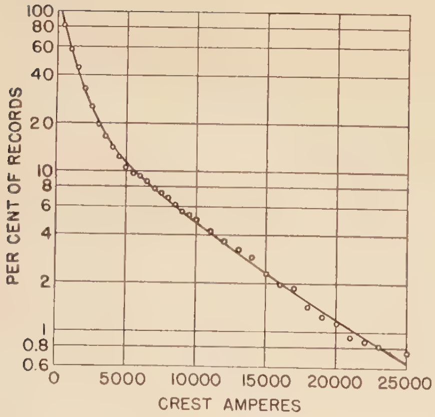

Figure 1. Summary of all records

Half of the 1,608 records were of currents of less than 1,300 amperes. Curve shows per cent of discharges whose magnitude was at least as great as indicated

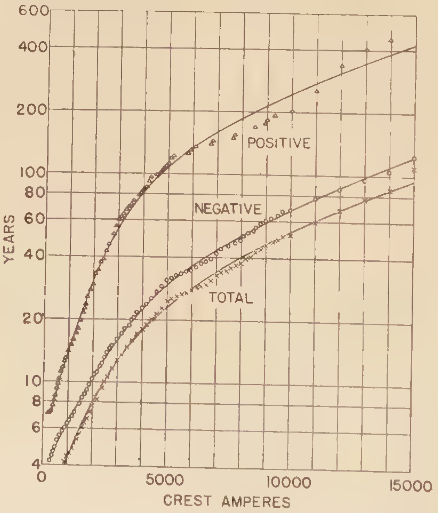

Figure 2. Comparison of 597 positive and 1,101 negative records from 4,036 installation-years

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

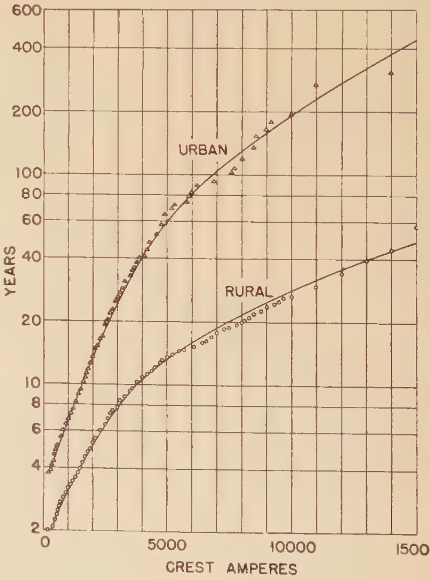

Figure 3. Comparison of 588 urban and 925 rural records from arrester ground leads

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

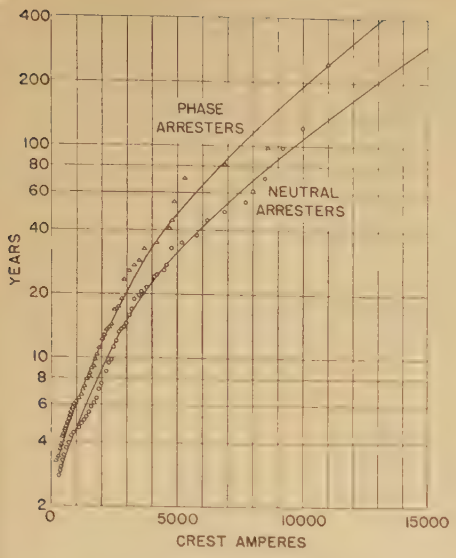

Figure 4. Comparison of 166 records from six-kv phase arresters and 189 records from three-kv neutral arresters on circuits of the Boston Edison Company

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

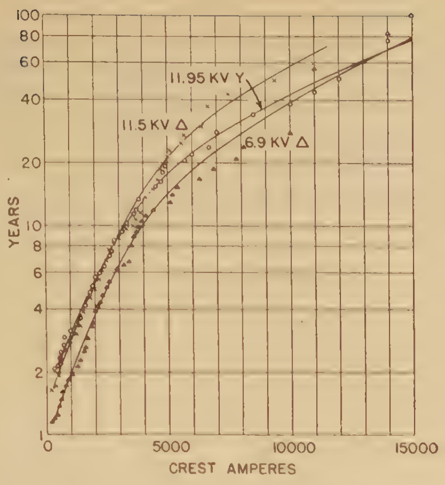

Figure 5. Comparison of results from Georgia Power Company circuits of different voltage ratings

151 records from 6.9-kv circuits
192 records from 11.5-kv circuits
155 records from 11.95-kv circuits

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

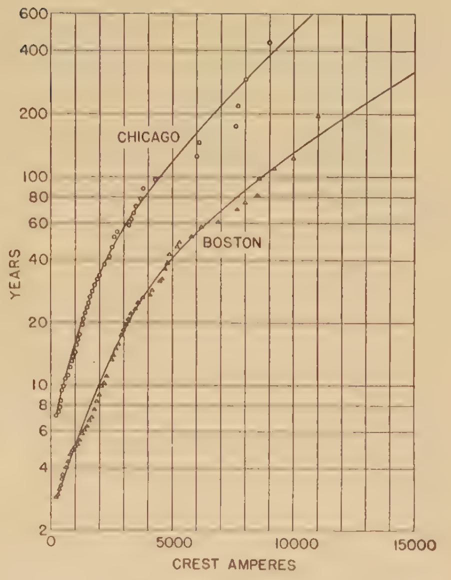

Figure 6. Comparison of 123 urban records from the Commonwealth Edison Company of Chicago and 365 urban records from the Boston Edison Company

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

however, from figure 4 there seems to be a definite tendency for the current to be 20 to 30 per cent greater through the neutral arrester. Some difference in current would be expected in those cases where the two arresters are effectively in parallel, and the discharge current may divide between them according to their resistance. Because of their lower average rating, the neutral arresters would have lower resistance and would pass higher current in such cases.

Effect of Circuit Rating

There seems to be no definite effect of circuit rating upon arrester discharge currents, although as shown in figure 5 there is a slight tendency for the lower rated arresters to carry a current of a given value more frequently. All of the data in this figure come from rural installations of the Georgia Power Company, all within the same state and presumably with about the same degree of exposure. The differences between the curves are too small to be more than an indication of what to expect, since a great many unknowns influence the results.

Effect of Location Upon Number of Records

For a given locality, the number of records per month seems to vary almost in proportion to the number of storms in that locality. However, as between localities, the correlation is not good.

A comparison between the results of 976 installation-years in Boston and 874 installation-years in Chicago is interesting. In Boston the currents are through three-kv and six-kv arresters used as neutral and phase arresters, while in Chicago the results are based on current measurements through three-kv phase arresters. Three hundred and sixty-five records were obtained in Boston compared to 123 obtained in Chicago. The expectancy curves of figure 6 indicate that a current of at least 10,000 amperes will occur in Boston about three times as often as in Chicago, in spite of the fact that an average of 15 thunderstorms per year were reported by weather bureau stations near Boston, and 45 per year at Chicago during the period of the investigation. These results seem to indicate that as far as records of arrester discharge currents are concerned, some other factor than number of storms per year exerts a major influence. A similar difference was found for the first 13 months of the investigation, and it was suggested by the authors that the difference might be due largely to difference in exposure. In Chicago the shielding is undoubtedly much more effective than is the case in Boston where the installation might more properly be classed as suburban. The difference is possibly due in part to less frequent checking of the magnetic links in Chicago. Most installations there were checked only once a year. However, since most of the links remained unmagnetized even at the end of that period, it does not appear likely that there was much superposition of records.

From the above it follows that the prediction of arrester currents upon the basis of thunderstorm data, in a locality where current measurements are not available, is not likely to lead to a very satisfactory result. The 20-year isokeraunic map[4] of the Weather Bureau indicates about 40 storm days per year in Chicago compared to 20 in Boston.

A comparison may also be made between the records obtained on rural circuits in Georgia and Detroit. Figure

7 summarizes 490 records from 765 installation-years in Georgia and 419 from 1,004 installation-years in the vicinity of Detroit. Although the frequency of discharges of all magnitudes is 1.5 times greater in Georgia than in Detroit, the frequency of high-current discharges is greater in Detroit, being three times as high as 15,000 amperes.

LIGHTNING SEVERITY BY MONTHS AND BY YEARS

In figure 8 is given the lightning severity by months, based upon the total number of records obtained, the number of records greater than 5,000 amperes, and the thunderstorm data for Boston and Chicago. In each case the charts show the percentage of the year's total lightning occurring in each month.

Figures 9 and 10 give the relative severity by years in the four locations; i.e., Georgia, Detroit, Chicago, and Boston, based upon the total records and those above 5,000 amperes. Values are given in per cent of the overall average for the four locations for the period of the investigation. Here again it should be remembered that links were checked less frequently in Chicago and this may have resulted in some decrease in the apparent severity.

RELATIVE SEVERITY IN DIFFERENT LOCATIONS

The greatest number of records per installation (figure 9) was obtained in Georgia each year but 1937, the average to date being about double that of the next highest, the Detroit Edison Company. For records above 5,000 amperes (figure 10) the Detroit Edison Company has the highest average. Although the Georgia records are twice as great in number as the Detroit records, above 5,000 amperes the Detroit records are about 30 per cent more numerous. A similar situation exists between Detroit and Boston, the average number of records being approximately equal, yet the number of records above 5,000 amperes being about four times as great in Detroit as in Boston. This seems to indicate that lightning strokes are more severe in Detroit or else the line construction is such that a higher level of line insulation is maintained. The Commonwealth Edison data cannot be used to good advantage in this comparison, because the circuits are so predominantly urban.

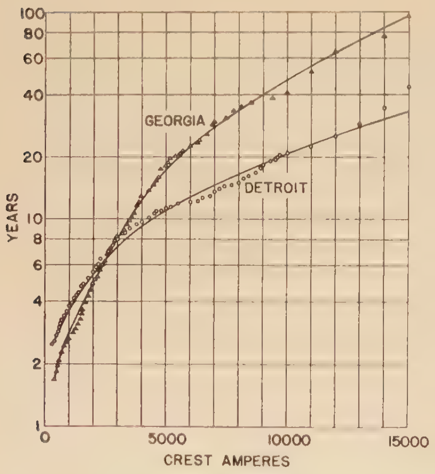

Figure 7. Comparison of 490 rural records from Georgia Power Company and 419 rural records from the Detroit Edison Company

Curves show the number of years that may be expected to elapse for each discharge of at least the magnitude indicated, through any one arrester

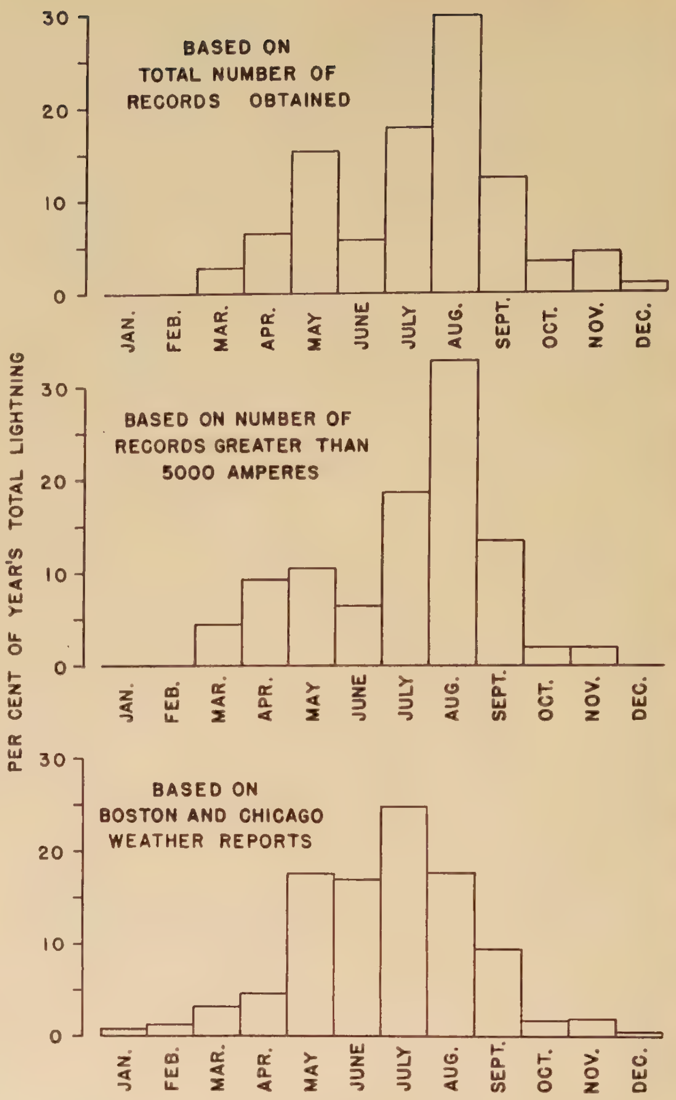

Figure 8. Relative lightning severity by months

There seems to be a persistent feeling among operating men that although the storms are less frequent in the Middle West than in the South, the strokes are more violent and do more damage. The Detroit data tend to support this contention, as far as the severity of strokes is concerned. Damage to apparatus was, however, much more frequent in Georgia.

ARRESTER AND TRANSFORMER FAILURES—FUSE BLOWINGS

There has been much speculation as to the performance of lightning arresters when subjected to natural lightning currents of different values, with regard to the protection offered and the effect on the arrester itself. Figure 11 shows the operating record of arresters for all four systems. With 3,787 installation-years involved, the arrester failure rate is 0.66 per cent per year. These data of course include arresters of all makes and ages. Exclusive of Georgia, the failure rate is 0.27 per cent per year, which is a very satisfactory record.

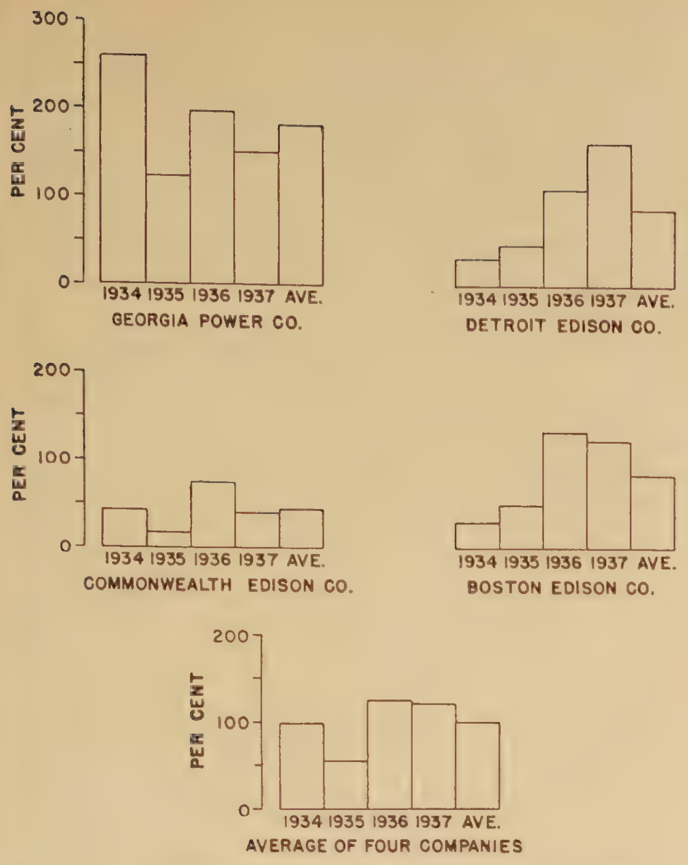

Figure 9. Relative lightning severity by years based on total number of records obtained

Values shown for 1934 and 1937 cover only a part of the year

There is some tendency for the failure rate of arresters per record to increase as the current increases, although this is not apparent to any extent if the Georgia data are excluded. Sixty-eight per cent of the arrester failures occurred in Georgia, despite the fact that Georgia had but 34.5 per cent of the total records.

Of the 12 records above 25,000 amperes, two are associated with one transformer failure. There were no arrester failures associated with these high currents. As to the distribution of these high currents with respect to location, one came from Chicago, two from Georgia, three from Boston, and six were obtained from Detroit.

Eighty-four per cent of the arresters under study were interconnected in 1937, but no segregation of data is attempted since the number not interconnected is too small to yield definite conclusions. Possibly the transformer failure record would have been even better than it is, if a larger number of arresters had been interconnected.

The data show 36 fuse blowings, of which 28, or 78 per cent, were reported from Georgia. There is some tendency for the percentage of fuse blowings per record to increase with increasing arrester current, but as with the arrester data, this effect is practically nonexistent if the Georgia data are excluded. This may be explained by the fact that at some of the Georgia locations, the fuses were ahead of the arresters. They would therefore be called upon to pass all impulse currents which went to ground through the arresters, and the high-current discharges may in themselves be sufficient to blow the fuses.

Of the 17 transformer failures, 13 were in Georgia giving an over-all failure rate of 0.72 per cent of the installed transformers per year, and excluding Georgia, a rate of 0.21 per cent. Why the Georgia trouble rate is higher than the others is not clear, although it is partly explained on the basis of increased frequency of lightning discharges.

Conclusions

1. Within the limits of this investigation, circuit rating seems to have but little effect upon the frequency of occurrence of arrester discharges of a given current magnitude. If any conclusion is to be drawn, it is indicated that the lower rated arresters tend to carry more current, or to carry a given current more frequently.

2. Fifty per cent of the currents measured were found to exceed 1,300 amperes, while 0.75 per cent exceeded 25,000 amperes. In the current range from 5,000 amperes to 15,000 amperes, negative currents were found about 3.5 times as frequently as positive currents. The smaller ratio of negative to positive discharges compared to measurements on transmission line towers may be due to the lower height of the distribution circuits.

3. The rural arrester must discharge currents of the

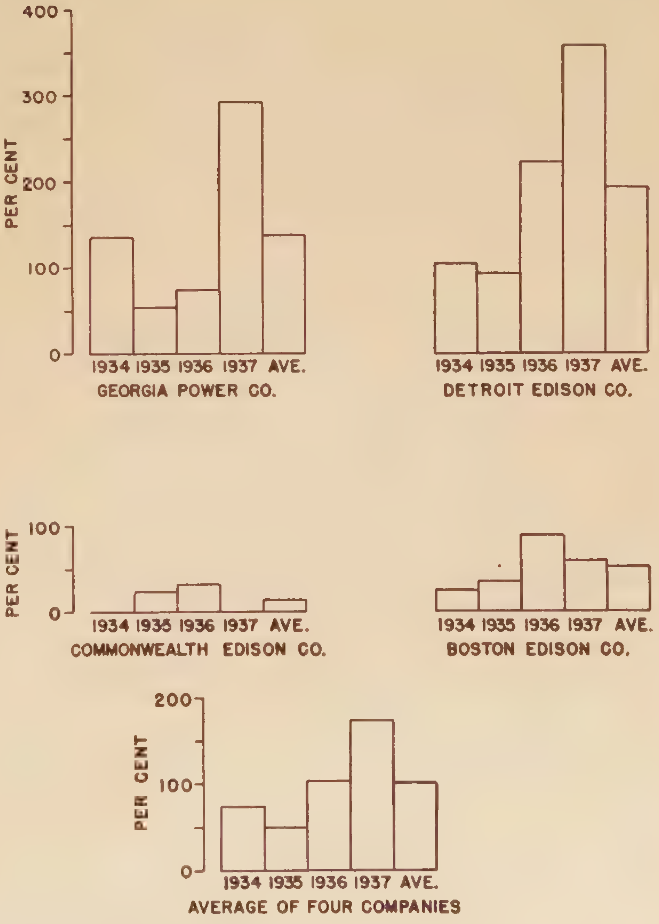

Figure 10. Relative lightning severity by years based on number of records of currents greater than 5,000 amperes

Values shown for 1934 and 1937 cover only a part of the year order of 500 amperes twice as often as the urban arrester, while at 15,000 amperes the ratio is increased to nine to one. The rural arrester must discharge a current of 15,000 amperes or more once in 50 years and the urban arrester once in 450 years.

4. There does not seem to be any satisfactory method for translating Weather Bureau thunderstorm data into the number of arrester discharges to be expected. In a given locality, however, the variation in the number of records agrees fairly well with the variation in the number of storm days.

5. In general the largest number of arrester and transformer failures and fuse blowings occur with relatively small currents of 3,000 amperes and less. This may be due in part to the great preponderance of currents of this magnitude. Excluding one system which had a much higher trouble rate than the others, there seems to be little if any tendency for an increased arrester failure rate with increasing currents. None of the 12 currents in excess of 25,000 amperes caused arrester failure, although one transformer failure was associated with two of the high current registrations in Boston.

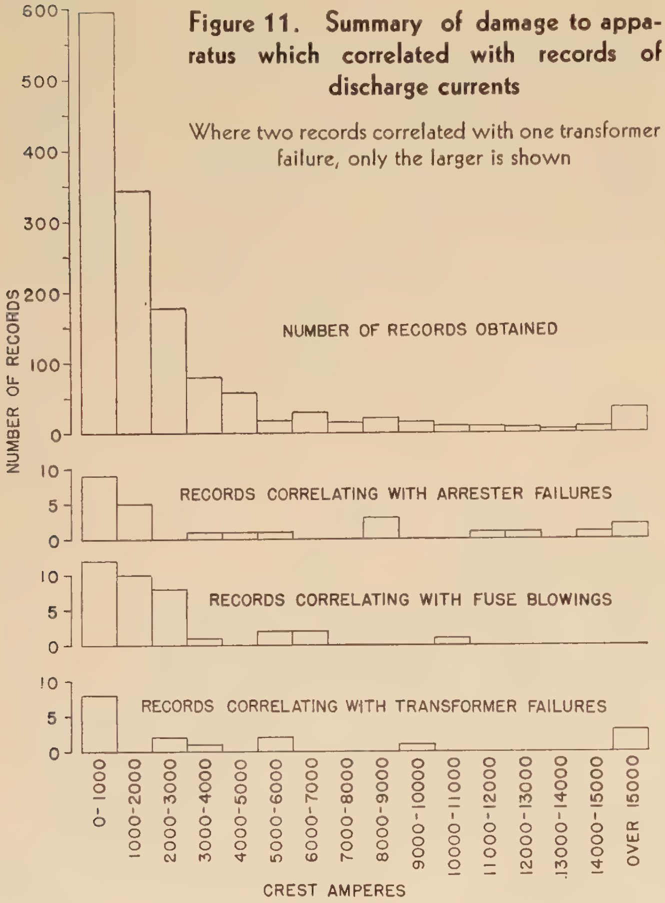

Figure 11. Summary of damage to apparatus which correlated with records of discharge currents

Where two records correlated with one transformer failure, only the larger is shown

6. Since the investigation covered a little over three lightning seasons in four different localities, considerable confidence can be placed on these results for design purposes. Proper consideration must of course be given to the circuits and localities involved, and to the limitations of the methods used in making this study.

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Discussion

W. G. Roman (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The data this paper presents are valuable to the arrester manufacturer in designing an arrester which can discharge lightning surge currents without damage to the arrester itself and at the same time afford adequate protection to distribution equipments. The arrester's record so far is good, but continued efforts should be made to improve it both in design and in the method of application.

It is interesting to note that of the 12 records above 25,000 amperes none were associated with arrester failures. This indicates that the distribution arrester has a discharge capacity sufficient to handle even the more severe lightning surges.

Can the higher trouble rate experienced in Georgia be co-ordinated with the type of protective scheme used or the ground resistance of the average arrester installation? As the authors point out, the lightning discharge frequency is higher in Georgia than on the other systems, but their trouble rate is higher than can be accounted for by this increased frequency.

The magnetic-link surge-crest ammeter has given much valuable data on lightning surge currents. A need is felt for data of this type on the duration of the surge current as well as the crest value. Has the General Electric Company any data on the type of record which would be obtained with a magnetic link inclosed in a conducting or semiconduction sheath? Currents induced in this sheath would tend to prevent the link being magnetized. On short surges this effect would be greater than on long surges of the same crest current and it might be possible to use this link co-ordinated with an unshielded link indicating crest current to give an approximate indication of the length of the surge.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.): The magnitude and frequency of lightning currents in distribution arresters actually measured in the field, as reported by Messrs. McEachron and McMorris, show how far short our present AIEE Standards fall in setting up standards for impulse tests of lightning arresters. The authors' paper (figure 1) shows over 40 per cent of the recorded currents above 1,500 amperes (the maximum value mentioned in the Standards); ten per cent are above 5,000 amperes and five per cent above 10,000 amperes, with maximum recorded currents of 25,000 amperes.

Certainly the users of lightning arresters want to know what degree of protection the arrester is capable of supplying at these higher currents so that they may co-ordinate, on a sound and economical basis, the arrester protective level with the apparatus it is intended to protect. In the none too distant past it must be admitted the application of arresters for protection was more on a catalog basis of system voltage rating rather than on the basis of establishing a protective level known to be below the safe strength of the apparatus.

As more data of the type presented in this paper are obtained, including rates of voltage and current rises of natural lightning on electric systems, it is hoped our knowledge of the protective characteristics of the arrester will be extended to cover at least those conditions which are known to exist in the field.

The authors mention 36 cases of fuse blowings. I would like to ask if they can tell us the current rating of these fuses, or the approximate rating. In other words does field experience, from these tests, give any information on fuse sizes which do or do not blow under known lightning currents?

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): An essentially statistical investigation of this type gains progressively in value as the number of results accumulates. It has now reached the stage where reliable conclusions may be drawn. We feel, however, that the interpretation of some of the results is open to question.

With 976 installation-years, Boston obtained 365 records, while with 874 installation-years Chicago obtained 123 records. This was in spite of the fact that the Weather Bureau reports 15 storms per year at Boston as compared with 45 storms per year at Chicago. Most installations in Chicago were checked but once a year, while the checkings were more frequent in Boston. The fact that most of the links remain unmagnetized at the end of a year is no assurance that there was a negligible amount of superposition of records.

An excess of superposition over the amount computed, assuming the records to obey a statistical distribution, is to be expected, because, first, in a given year certain locations in a large city will be located in a larger proportion of storm centers than others and, second, due to less shielding by neighboring buildings some locations may have a considerably greater a priori probability of being struck than others.

At 22 locations in Chicago the links were checked four times during 1936; 12 records were obtained, assuming no superposition to have occurred in the short intervals between inspections. If the installations had been checked but once in 1936, it appears that only eight records would have been found. In other words, in order to obtain the correct number of records, at least 50 per cent would have to be added to the observed number as obtained on the yearly basis.

This superposition is much greater than would be predicted under the assumption that all locations were equally susceptible to lightning during 1936. The straight application of the Newton formula to the data would indicate that 1.8 records had been lost while the number actually lost was four. The data obtained in 1937 at these same 22 locations gave similar results. In this year the number of records actually lost by superposition was four times the computed number.

It is not our contention that the apparently abnormally low lightning severity in Chicago is completely to be explained by superposition of records. The effect of the better shielding conditions in Chicago, as suggested by McEachron and McMorris, may explain the balance of the discrepancy.

The highest current shown in figure 6 for Chicago, i.e., 9,000 amperes, was for an installation having standard arrester connection and $10\frac{1}{2}$ ohms ground resistance. Apparently at the time of the discharge, an old three-kva transformer failed, but the old-type arrester at this location did not fail. This is another experience showing that the arrester standards should specify a much higher current than 1,500 amperes for acceptance tests on modern-type arresters.

L. G. Smith (Consolidated Gas, Electric Light and Power Company of Baltimore, Md.): The data being collected by the authors are of considerable value in designing the lightning protection of distribution systems and determining the necessary discharge capacity of lightning arresters applied to such systems. However, in order to be of conclusive value it requires the collection of a considerable amount of data. The 1,352 installations constitute a very small sample of the total number of installations of distribution lightning arresters. It is highly desirable for more companies to co-operate so as to increase the number of installations and spread and coverage of the territory represented by these installations. However, before definite conclusions can be drawn, many more years of collection of data will be required. The industry is greatly indebted to the authors for undertaking such a valuable study.

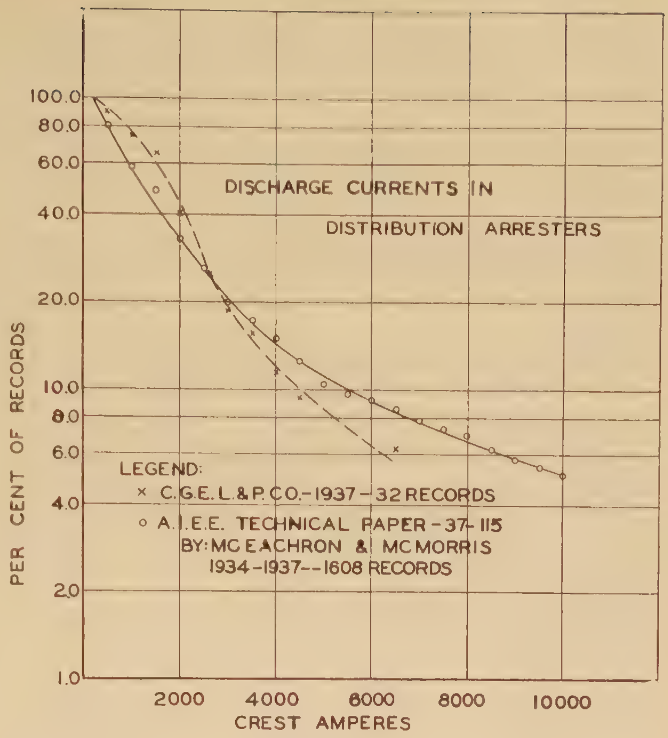

Figure 1

Last summer our company installed surge-crest-ammeter links at 150 distribution-arrester locations. As these installations were completed late in the summer, data were obtained for only two lightning storms. However, 32 records were obtained. The maximum surge amperes recorded were 6,500. Surge currents as low as 500 amperes were recorded. As a matter of interest our meagre data was plotted on the curve shown by the authors in figure 1, in order to determine how closely our data conformed with the more voluminous data collected by the authors. These two curves show remarkably close agreement for the small number of records obtained by our company. We plan to continue the collection of these data over a period of several years.

C. Francis Harding (Purdue University, Lafayette, Ind.): In addition to my discussion of the similar paper by L. G. Smith entitled "Distribution Transformer Lightning Protection Practice—II" it should be noted that the results of this statistical field analysis also confirm the predictions based upon the experimental tests of the four-span standard distribution system subjected to surge generator exposures at Purdue University under the auspices of the Public Utilities Research Commission of Chicago.

The record reported in this paper of relatively high surge currents in the arresters located on rural distribution circuits indicates that the attenuation of the wave along such circuits is not as great as anticipated and that the magnitude thereof should be more seriously considered in establishing higher current testing standards by the lightning-arrester subcommittee.

K. B. McEachron and **W. A. McMorris:** Mr. Halperin presents some interesting results based on data obtained in 1936 at 22 measuring locations, where links were checked four times during the lightning season. It is indicated that with annual inspection of links, the number of records lost by superposition would have been at least four, but the number predicted on the basis of equal exposure of all locations would have been approximately two. If only two less records had been obtained, this discrepancy would disappear. The 1937 results were based on a smaller number of records.

We have not been able to identify exactly which measurements Mr. Halperin refers to, but they apparently include some readings from the few special installations on common ground leads, interconnection ties, or neutral arresters (gaps), which would be expected to have greater exposure than installations on phase arresters. Links were checked more frequently at these locations because of the special installations there.

We do not feel that in a statistical investigation of this nature, a difference of two or three records one way or the other is a sufficient basis for very definite conclusions. The following analysis based on a larger number of installations over a longer period of time may be of interest.

In Chicago 236 of the installations on phase arresters on 4-kv circuits have remained in their original locations since the beginning of the investigation. They have produced a total of 104 records. If it is assumed that all locations have equal exposure to lightning, the distribution of records may be calculated from the law of independent trials. The number of locations each of which would be expected to produce exactly k records may be determined from the expression

$$n_k = n\frac{m!}{k!\,(m-k)\,!}\left(\frac{1}{n}\right)^k\left(1-\frac{1}{n}\right)^{m-k}$$

where

m = total number of records, and

n = total number of locations.

The actual and calculated distributions for Chicago are as follows:

k Records per Location	Number of Locations With Exactly k Records Each	
	Calculated	Actual
0	151.8	151
1	67.2	67
2	14.7	17
3	2.1	1
4	0.2	0

The agreement between actual and calculated distribution is surprisingly good. The same is true for the Detroit and Georgia records, and to a lesser degree for the Boston records. This agreement indicates that the distribution of records has not been greatly influenced by factors which have not been taken into account and therefore that no great error would result from using the theory of probability to predict the number of records lost by superposition.

When $k = 0$, the above equation reduces to

$$n_0 = n\left(1-\frac{1}{n}\right)^m$$

solving for m,

$$m = \frac{\log n - \log n_0}{\log n - \log\,(n-1)}$$

This equation will permit us to estimate the number of records lost by superposition. If we let n_0 represent the total number of installations at which links remained unmagnetized after a given period of exposure, then m represents the expected total number of discharges during that period. The number of records obtained would be equal to $(n - n_0)$, so $m - (n - n_0)$ would be the number of discharges which were not recorded because of superposition. The curve in figure 2 herewith is based on this relation. It does not account for the later discharges of a multiple stroke, which are not free to discharge through any path at random, but have a very strong tendency to follow the first discharge of the series.

Several who have discussed this paper have brought out the point that the present standard AIEE impulse tests are not representative of the most severe discharges measured in service. Field data on the arresters involved in the investigation do show, however, that the arresters which have the best protective characteristics on the AIEE test have given the best account of themselves under service conditions.

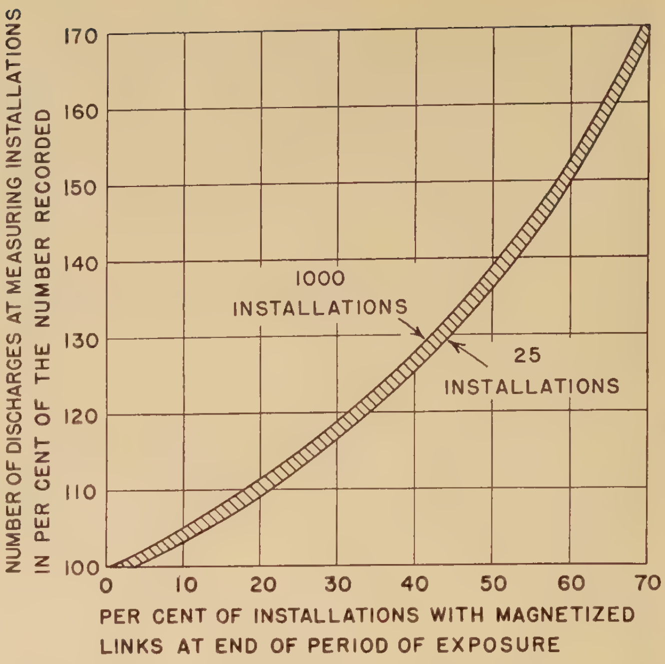

Figure 2. Effect of superposition of records on the number of discharges actually recorded, assuming that it is equally probable for any discharge to appear at any measuring installation

Mr. Gross has inquired about the ratings of fuses which were reported to be blown. These extended from two amperes up to 30 amperes. The rate of fuse blowing was higher for those locations where the fuse was ahead of the arrester, so that arrester discharge currents were carried by the fuses. Some of the fuse blowings are believed to have resulted from overloads due to secondary faults, rather than from lightning currents alone.

There is great need for more data on the duration of impulse current waves, as pointed out by Mr. Roman. We have considered the method of measurement he proposes, as well as other similar methods, for adapting magnetic links to give an approximate indication of wave fronts and duration. Laboratory tests have been made over a period of several months to determine the best constants for the sheath, and to obtain calibration data.

This method is attractive because it is so simple and inexpensive to apply. The interpretation of records is however quite complicated, and only approximate results are obtained, because of the large number of variables involved. It may prove desirable to make installations of this type, but it is hoped that other equally inexpensive methods may be developed for obtaining information more easily interpreted into accurate values for wave shape and duration.

We do not have sufficiently complete data available to justify definite conclusions as to the causes of higher arrester and transformer failure rates in Georgia. Some of the ground resistances were, however, relatively high. The use of longer leads from secondary neutrals to arrester grounds may have contributed to the higher trouble rate.

We are pleased that others are undertaking investigations of this nature and that the results already obtained by Mr. Smith are in general agreement with what we have reported. The accumulation of more data will more firmly establish what duty is imposed on a distribution arrester in different types of service.

Since the scope of the investigation has been limited, it may prove more advantageous to alter it to obtain more information on the few discharge currents above the present measuring range, to include other localities or types of circuits, or to obtain information on the wave shape or duration. A given amount of work may bring greater returns to the industry if directed along these lines, than by merely continuing at the present locations with no changes.

Results of Operation of PCC Cars in Pittsburgh

By T. FITZGERALD
ASSOCIATE AIEE

THE Pittsburgh Railways Company has purchased 201 cars of the Presidents' Conference Committee type. By the middle of November 1937, there had been delivered and placed in service 140 of these cars. The new vehicles have exceeded our expectations with respect to their mechanical performance, their reception by employees, and the approval given them by the public.

The company placed its first order, consisting of 100 cars, in July of 1936. Of these, 75 units are equipped with Westinghouse motors and control apparatus, and 25 are General Electric equipped. The same distribution was made on the second order.

Prior to the delivery of any units of the first order, we obtained a sample car which we used to demonstrate to the public the superior qualities possessed by this outstanding advance in vehicle design. We operated this sample car in demonstration service from August until December, in which period we carried 25,000 passengers free, and it was inspected by uncounted thousands on the streets. This period of operation also gave our mechanical department an opportunity to study its design and to devise methods by which to cope with such difficulties as developed. The preliminary study and experience thus obtained by the mechanical group were of great value, in that they were well prepared to test the cars as they arrived, and to adjust them to give the performance of which we knew the car to be capable.

The design of the PCC car incorporates features which we in Pittsburgh had felt for a long time were essential in a trolley car if it were to compete effectively with the private automobile and the bus. The principal deficiencies of the cars we had were excessive vibration and noise; inadequate deceleration; inadequate, jerky acceleration; and unnecessary weight. We had a little speed, which we obtained by rewinding the motors on about half of our cars, which increased their power by 50 per cent and their free running speed from a maximum of 30 miles per hour to a maximum of 40 miles per hour, an increase of $33^1/_3$ per cent. On a six-per-cent grade, the speed improvement of the higher-speed cars was 50 per cent. When the cars were converted to higher speed, we increased the braking efficiency and performed other work on them designed to make the car in general conform with its higher speed characteristics.

It will be noted that the operating characteristics of the rewound-motor cars approach those of the PCC cars, so that we are able to place both types of cars in a schedule without losing the efficiency of the new car, and with reasonable assurance of maintaining the schedule.

Delivery of our first order of cars commenced in late January of 1937. At the outset, we had to decide whether to fully equip a route with the new vehicles, or to equip the base service of the route selected, and use cars with rewound motors to supplement the service for the peak haul. We decided on the latter plan, because we could thereby get a greater coverage of the system, and also keep the new cars in service to a greater extent. If the new cars had been used to fully equip a route, the peak cars would have been idle the greater part of the time. By applying the cars to base and evening schedules only, we were able to equip ten routes with the first group, and we will equip 13 routes with the second 100 cars.

At the middle of November, we had a total of about 3,440,000 miles of operation on the first group of cars, and 60,000 miles of operation on about one-third of the second order, which began to come in during the latter part of October. Our method of application results in securing about 1,000 miles of service per week on each car, or 50,000 to 52,000 miles annually.

We have had less mechanical trouble with these vehicles than with any new car we have had on the property. We have had troubles, of course; none, however, which were fundamentally serious, or for which the engineers have not been able to devise remedies. In the light of the severe operating conditions which the Pittsburgh district offers, and the far-reaching changes in car design incorporated in the vehicle, it is to be wondered why we have had comparatively so little difficulty with them.

Evidence of how the cars are standing up in service is furnished by the weekly mileage of 1,000 miles which they are averaging. At ten miles per hour, that means they are averaging better than 14 hours of service per day, exclusive of time standing as spares, and of time required for routine inspection and cleaning.

Earlier, I indicated that noise reduction was an important advantage which we expected from the new design. The new car has advanced a long way in this regard, but it has made us acute to new noises which will have to be corrected. A short time after the cars were delivered, it was noted that a distinct and irritating rattle developed when crossing special track work, and when going over track irregularities. The source of the noise was found to be the bearings of the brake-shoe hangers on the brake-beam. Rubber was introduced into the design to eliminate the difficulty. Altogether, the noise level of the car is a tremendous improvement but it is not as good as we should seek to make it.

When we purchased the new cars we experienced some anxiety over the hypoid gears with which the cars are driven. Our experience has been such as to convince us that our fears were unfounded. So far, we have had only

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five gear failures and each was traceable to omitted lubrication which maintenance routine will overcome.

We have had no failures of resilient wheels except those which were damaged because hand brakes had not been fully released, or because the required pressure was not properly maintained on the rubber sandwiches incorporated in the wheel.

We have had little or no trouble with motor generator sets. The wear on rail brake shoes has been very slight. We feel we are getting good wearing properties out of our rail brake shoes, largely because our technicians have made the dynamic brake properly do its job. We are obtaining from four to five times the mileage on wheel brake shoes and they cost a little more than twice the cost of regular brake shoes. We originally estimated we would obtain about 60,000 miles of service from the resilient wheels of the PCC cars. Indicated wear at the present time is about 100,000 miles for one-half inch of wear, which is the limit of wear obtainable. This compares with 140,000 miles on regular wheels for two and one-half inches of wear. Due to the limited wear on shoes and wheels, there is considerably less labor required in resetting brakes.

We have had two derailments in 3,500,000 miles of operation, due to mud on the tracks, carried there by severe storms, and one derailment due to a broken propeller shaft. We have had one split switch caused by an object in the switch, and one split switch probably caused by excessive speed. I personally feel that these cars are going to hold the rails longer, not only in the sense of avoiding derailments and split switches, due to the resilient wheel, but also in the sense of demonstrating the value of rails in transit service and re-establishing the prestige of that type of service.

We have not made any changes in schedule speeds on the routes where the cars were installed, largely because the schedules were designed for and operated by the higher-speed cars which I have mentioned. The higher-speed schedules are, however, about 15 per cent better than is obtainable with the standard slow-speed cars.

Power consumption on the PCC car is, by test, about the same as that on the higher-speed car, and it is 25 per cent greater than on a standard slow-speed car. We will save considerable on heat, however, with the PCC car, over the conventional car. We use electrical space heaters on the old cars, and the new cars of course use the heat dissipated by the control resistors during acceleration and dynamic braking to heat the cars. We have ample heat in the new cars; in fact, we are receiving complaints of excessive heat, whereas the old cars are complained of as being cold, on days when extremely low temperatures prevail. We are not in position to estimate the effect of this on power consumption until we go through a winter with the new cars.

The PCC cars we have are all of the foot-control type. Although we had experimented with foot control on seven cars, it is the first time we have had a considerable number of cars of that type in operation. In qualifying trainmen on the new cars, we found that on the average about four hours of practice is all that is needed. The reaction of trainmen to the car has been universally good. They like them because of their smooth performance characteristics, the adequacy of the brakes, and the resultant ease of schedule maintenance, and because lost time can be recovered so much more easily with the new car. The only difficulty in operation so far encountered is glare in the windshield at night, particularly on wet nights. This is due to the bright interior, and we have mitigated this difficulty by various methods, such as dimming the cab lights, cutting off floor reflection, blacking the windshield frames, and on the second order of cars provision is made for a curtain which can be drawn about the operator's position.

Of course, the true measure of the new car rests in the effect upon revenues and the effect upon costs. We have seen enough of the car to lead us to feel that the costs will not be higher than with the conventional car and, if anything, the new car will produce an economy in track maintenance, power costs, and in costs peculiar to the car itself.

So far, the public response to the vehicle has been splendid. We have received many communications from patrons, who have been pleased with the improved service; and from civic and municipal groups, congratulating the company on the new vehicle. We are constantly receiving inquiries as to when the new cars will be installed on other routes in the system, which is another evidence of their popularity. The noise-reduction qualities of the new car have accentuated complaints of noise from older cars. I have for a number of years held the opinion that much of the lack of prestige of street cars was traceable to the noise attending their operation. The items of superiority of the new cars over the older cars most frequently mentioned are its quiet operation and its smooth performance.

I will now turn briefly to the patronage results on the routes where we have installed the new cars. I am sorry that we cannot speak more definitely about the increased patronage they have attracted. Further, I must confine my remarks to results on the routes on which the first 100 cars were installed, because we have had insufficient experience, up to this time, on the second group to record any patronage results.

The picture on three of the routes on which new cars have been installed has been confused by the fact that we made fare concessions at about the time the new car service was inaugurated. On certain of the routes, territory is served which is also served by other routes which do not have the new equipment, so that it is possible that certain patrons may use either route. In the studies which have been made, we have endeavored to adjust as nearly as we can for the factor of competition of the new cars with the older cars. On two routes on which the new cars have been installed and where a fare concession also was made, there has been no reduction of revenue—on the contrary, the route earnings have shown an increase. The fare reduction which was made was of substantial proportion.

It should be remembered that thus far where the new cars were installed, we previously operated higher-speed cars, which in themselves had a tonic effect upon revenues.

The new cars, of course, have provided a much improved performance and appearance, and to that we must ascribe the added traffic obtained. A property which has not speeded up its service will, in my opinion, secure the advantage of traffic stimulation from the greater speed of the PCC car. We began our program of conversion of cars to higher speed at the start of the depression, and we continued the program during the depression. We found that the routes which were equipped with the higher-speed car held their patronage better than others—an advantage, of course, which the recent installation of PCC cars does not give us in the making of comparisons.

The installation of new cars commenced on February 4, 1937. Two days later, on February 6, the rate schedule of the Pittsburgh Motor Coach Company was reduced from 25 cents cash, nine tickets for $2.00, to 15 cents cash, eight tickets for $1.00, and 20 tickets for $2.00. The routes on which the rate change took place had been originally designed to furnish a service supplemental to the rail service, and in most instances they occupied the same streets or closely paralleled rail service. It can be readily appreciated that with such a sharp reduction in fare, traffic on the busses was stimulated. Many of the new car routes have been up against this bus competition, and they have shown revenue improvements despite this unfavorable circumstance.

Data we have obtained to determine increased patronage shows that the new cars have been responsible for improvements ranging from 5 per cent to 11 per cent.

When consideration is given to the elements which affect the comparisons, such as bus competition, previous higher-speed schedule service, and installation in the spring of the year when traffic normally is on the decline, I feel that we have had a very favorable patronage response to the new car.

Our experience with the mechanical and electrical performance of the PCC cars has been better than we expected and is satisfactory. The cars have the performance to attract and hold patronage, and in my opinion they are an adequate answer to the charge of obsolescence of street railways. Continued improvement in the vehicle, which is inevitable, will, I believe, result in complete rehabilitation of the prestige of the street car as the most efficient and economical carrier where traffic demands heavy enough to justify that vehicle are encountered.

Discussion

R. E. Hellmund (Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.) [**Editor's Note:** This discussion covers also "The PCC Street Car," C. F. Hirshfeld, *EE, Feb. '38, Trans. p. 61–6*, and "Electrical Equipment for Modern Urban Surface Transit Vehicles," S. B. Cooper, *EE, Jan. '38, Trans. p. 50–6*]: The fact that the Presidents' Conference Committee car has attracted considerable attention in Europe may be of interest. Some of the visitors to the World Power Conference in 1936 had an opportunity to inspect the first Pittsburgh car and they were very much impressed not only by the technical features of the car but also by the arrangement which made its development possible. They felt that similar undertakings in Europe might be instrumental in bringing about renewed activity in electric street railways. When I visited Europe in 1937, I was surprised at the many inquiries made by the engineers regarding the PCC car, with reference both to generalities and to details, such, for instance, as the number of steps in the control, voltage per step which could be handled by the two types of control, etc.

As usual, it will for various reasons be difficult to directly apply American designs in Europe. For example, the narrow streets and sharp curves in many European cities are not suitable for a long two-truck car such as the PCC. There also seems to be some hesitancy in Europe to design motors for temperature rises and the very high speeds used in this country because experience along these lines is still lacking in Europe. Although for this reason developments may take a somewhat different course, I nevertheless believe that we can expect to see innovations in Europe which have been stimulated and influenced, at least to some extent, by the PCC car.

Operating Experiences With Gas-Electric-Drive Motor Busses

By R. H. STIER

THE Philadelphia Rapid Transit Company operates a co-ordinated urban transportation system serving the City of Philadelphia and adjacent suburban communities. The system is comprised of surface car, subway-elevated, motor bus, and trackless trolley lines. Motor-bus operation was started in September 1923, with 21 double-deck mechanical-drive busses of the "Fifth Avenue" type. At the present time a total of 323 busses are operated 12 million miles annually, and produce approximately nine per cent of the system passenger revenue. The busses operated include 138 33-passenger single-deck and 161 71-passenger double-deck gas-electric-drive busses purchased during 1925 and 1926. The remaining 24 vehicles are small-capacity 21-to-25-passenger busses, that have been purchased during the past four years.

Operating characteristics of the original 21 mechanical-drive double-deck busses, purchased in 1923, were most unsatisfactory from a passenger or transportation viewpoint. These busses were noisy and rough during acceleration, due to inherent characteristics of the clutch and transmission equipment. In order to determine means of improving the operation of these vehicles, the Philadelphia Rapid Transit Company investigated alternate drive mechanisms that could be applied to the motor bus.

It was learned that the General Electric Company had built ten double-deck gas-electric-drive busses for the Fifth Avenue Coach Company in 1904. In so far as could be ascertained operation of these vehicles was entirely successful. The experiment was abandoned, apparently due to reluctance of any of the automotive manufacturers to undertake construction of the gas-electric-drive bus, probably due to increased cost for the electric drive and limited market for motor busses.

During the interval between 1904 and 1923 the electric drive was not commercially developed, although isolated applications of the electric drive to automotive equipment were made, principally by the United States Army. Information available indicated that the electric drive offered the greatest promise of eliminating the objections of noisy and rough operation experienced with the mechanical-drive vehicle.

One of the "Fifth Avenue" type double-deck busses operated by the Philadelphia Rapid Transit Company was equipped with the electric drive. The apparatus was essentially identical to that still operated in 299 PRT busses, consisting of a separately excited four-pole generator similar to the GE 1098 machine, two series-wound variable-voltage four-pole motors similar to the GE 1079, and a simple three-position drumtype controller. Performance of the bus was improved to so marked a degree that the electric drive was specified for the 352 busses purchased by the Philadelphia Rapid Transit Company during 1925 and 1926.

During the early years of operation the usual trials and tribulations that go hand in hand with the pioneering of a new development were experienced. Operating problems were multiplied by the rapid growth that occurred in the Philadelphia Rapid Transit Company's bus operation, which was expanded from 527,000 miles in 1924 to 8,000,000 miles in 1926.

The problems were accentuated by changes in design of the vehicle, made during the early years of operation, which tended to increase the effective load on the electrical equipment. These changes included the replacement of the original 34-inch solid tires by 40-inch pneumatic tires on the double-deck busses and by 38-inch pneumatic tires on the single-deck bus; and the enclosure of the upper deck with resultant increased vehicle weight. The electrical apparatus was rebuilt to increase its capacity and improve its performance. Increased capacity improved performance of the equipment, but the basic cause of continued failure of the electrical equipment was attributed to use of noncommutating-field motors and generators. Commutator and brush wear was excessive and frequent flashover, with resultant damage to equipment, was experienced in service. After considerable study of the problem, in co-operation with engineers of the General Electric Company, methods of installing commutating field poles in the standard GE 1098 generator and GE 1079 motor were developed. Analysis of service data indicated that cost for this change would be justified in the GE 1098 generator, but it was doubtful whether the cost could be justified in the GE 1079 motor. During 1931 and 1932 the majority of the GE 1098 generators were rebuilt and commutating field poles installed. Mileage operated between reconditioning periods was increased from 32,000 for the noncommutating-pole GE 1098 generator to 107,000 miles for the commutating-pole GE 1098 generator.

Performance of the electrical equipment can be judged by analysis of maintenance expense, shown in table I. Maintenance expense for electric transmission equipment includes all costs for generators, motors, controllers, kilowatt-hour meters, and wiring. It will be noted that installation of commutating poles, during 1931 and 1932, decreased percentage of total maintenance chargeable to electric transmission equipment from an average of 17 per cent to an average of less than 13 per cent of total maintenance expense. Record of maintenance expense for these vehicles and for the electric transmission equip-

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ment, during recent years, is an outstanding achievement that can be largely attributed to the inherent advantages of the electric drive.

The Philadelphia Rapid Transit Company is now confronted with the necessity of replacing the greater portion of its bus fleet, 93 per cent of which is of the gas-electric type and has been operated between 11 and 12 years. In view of the imminent purchase of new bus equipment, the controversial question as to whether or not the electric drive should be utilized must be answered. Since 1924 extensive changes in design of clutch and transmission equipment have been made, that eliminate many of the objections to the equipment that were in part responsible for the original selection of the electric drive in 1924. Although majority of busses that have been operated are of the gas-electric type, operating experience with these vehicles is of little value in determining the type equipment best suited to the service requirements, since the vehicles are of obsolete design and construction, and since comparative service data is not available for the mechanical-drive bus. It is considered that a description of the analysis that has been made of the relative advantages and disadvantages of the electric-drive and mechanical-drive motor bus would be of greater interest than an elaboration of the operating experiences with vehicles of obsolete design.

Discussion of the relative merit of the electric drive will be predicated upon its use in frequent-stop heavy-traffic urban service for which it is basically adapted. The primary problem encountered, in weighing the relative advantages and disadvantages of the electric-drive and mechanical-drive bus is to secure authentic, comparative basic data. In order to secure the fundamental information required, tests were conducted with a number of modern busses of various types. For simplification we have limited the discussion to analysis of representative results obtained from performance tests of two 35-passenger busses of identical design and construction, differing only in that one vehicle was equipped with a conventional clutch and three-forward-speed, constant-mesh transmission; the other vehicle equipped with a GE 1501 self-excited generator and one GE 1205 series-wound motor. Both busses were tested with the equivalent of a seated passenger load, the mechanical-drive vehicle weighing 21,425 pounds and the electric-drive weighing 23,050 pounds.

Table I. Maintenance Expense for Gas-Electric-Drive Motor Busses

Year	Total Maintenance (Cents per Mile)	Maintenance—Electric Transmission Equipment: Cents per Mile	Maintenance—Electric Transmission Equipment: Per Cent of Total Maintenance Expense
1926	4.60		
1927	5.59		
1928	5.04		
1929	7.29	1.17	16.1
1930	5.86	0.90	15.4
1931	5.01	0.86	17.3
1932	4.03	0.85	21.1
1933	2.71	0.28	10.3
1934	2.76	0.34	12.3
1935	2.83	0.38	13.4
1936	3.23	0.42	15.0
1937*	2.75	0.30	10.9

* Ten months.

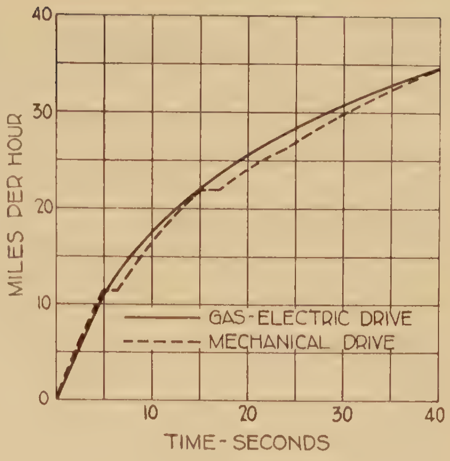


Figure 1. Acceleration characteristics

In order to eliminate, in so far as possible, the human element, a skilled and specially trained driver operated the vehicles during all tests. The test busses were equipped with special apparatus to measure performance. Acceleration and deceleration were measured by a Hasler-Tel recording accelerometer, which is essentially an integrating speedometer that records distance traveled in feet, time in seconds, and mean or integrated speed during each second. The meter was driven by means of a bicycle wheel, mounted on the side of the bus. Combustion efficiency was measured before each series of acceleration runs, with an Orsat exhaust gas testing apparatus. An electric tachometer measured engine speed.

Acceleration runs were operated over a 2,100-foot strip of concrete highway that had a slight but constant grade of 0.7 per cent. Runs were operated in each direction, and the average acceleration characteristics for the gas-electric and mechanical-drive busses are shown graphically, figure 1. It is evident from comparison of these speed-time graphs that instantaneous acceleration values for the mechanical-drive bus are slightly higher than corresponding values for the electric-drive bus. This advantage is more than offset by time required for gear changes in the mechanical-drive bus, with the result that road speed of the electric-drive bus is slightly higher over the operating range. For comparative purposes, the speed-time graphs for the two vehicles can be considered essentially identical. It would be concluded from a comparison of acceleration characteristics that there would be a negligible difference in relative scheduled speed ability between the electric-drive and mechanical-drive busses. This conclusion is contrary to normal operating experience, and further analysis is necessary to determine whether other factors affect the scheduled speed ability of the two types of vehicles.

Fuel consumption of the electric-drive and mechanical-drive busses was measured at varying stops per mile, under rigidly controlled operating conditions. Tests were made over a closed course having a measured distance of one mile. In order to minimize operating variables to the greatest possible extent, all tests were made with maximum engine performance, that is, with wide-open-throttle acceleration and no coasting. Operating speed and time were measured with a Hasler-Tel performance meter. Fuel consumed during each test run was accurately weighed, using a platform scale calibrated to 1/100th of a pound. Temperature and specific gravity of the fuel were also obtained in order to convert weight of fuel consumed into gallons.

Fuel consumption tests were conducted, with a fixed operating cycle of maximum acceleration between stops and a seven-second standing time at each stop, for various stop frequencies between four and eight stops per mile. The mile closed test course had been surveyed and stops were made at fixed points during the test runs. The comparative fuel consumption for electric-drive and mechanical-drive busses is shown in figure 2. Fuel consumption as determined by these tests indicated that use of the electric drive increased fuel consumption 22.9 per cent at four stops per mile and 23.1 per cent at eight stops per mile.

During tests to measure fuel consumption of each type bus, the elapsed time for each run was measured in order that scheduled speed at varying stops per mile could be calculated. The comparative scheduled speed in miles per hour for the electric-drive and mechanical-drive busses is shown in figure 3. It is apparent, despite the fact that the acceleration tests indicated negligible difference between the scheduled speed ability of the two vehicles, that the electric-drive bus constantly maintained a higher scheduled speed than the mechanical-drive bus. Scheduled speed operated by the gas-electric-drive bus was 6.4 per cent faster at four stops per mile, and 8.6 per cent faster at eight stops per mile.

Test data shown graphically, figures 1, 2, and 3, were measured under conditions controlled so as to insure to our satisfaction that measurement of performance characteristics were comparable between the two vehicles and that results could be duplicated between successive runs. We would not defend the accuracy of these measurements from an absolute or scientific viewpoint, but we believe that they may be used as a basis for predicting the relative differences in performance between the gas-electric-drive and mechanical-drive bus.

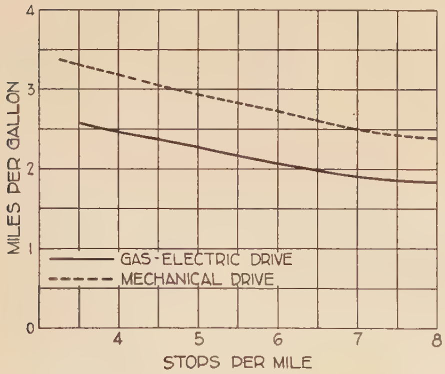


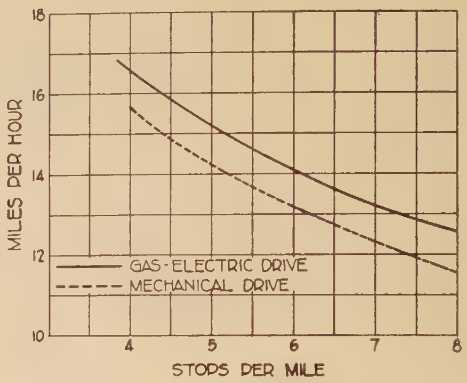
Figure 2. Fuel consumption

Selection of bus equipment is fundamentally a question of economics and in the final analysis the relative advantages of a particular type vehicle can and should be reduced to terms of dollars and cents. Comparison between the electric-drive and mechanical-drive vehicle can be made in terms of dollars and cents, predicated upon the results of the tests conducted, adjusted to take cognizance of operating experience. The problem may be reduced to a simple equation:

Net income per vehicle = total revenue − total expense

Since the only variable under consideration is the drive mechanism, analysis of those factors, inherent in the electric and mechanical drives, and the evaluation of their effect on revenue and expense, will indicate which of the two types of drive mechanism is best suited to the operating requirements. Many of the factors are indeterminate, but a qualitative estimate of their value may be approximated. Evaluation of these factors represents the personal viewpoint of the author, and it is acknowledged that there may be wide divergence of opinion as to the interpretation of the basic information herein presented.

Figure 3. Scheduled speed



Total revenue may be a function of the traffic promotional value or sales appeal of the vehicle. It would seem self-evident that the electrice-drive bus has a greater sales appeal to the public than the mechanical-drive vehicle. The quiet, smooth, and uninterrupted acceleration characteristics resulting from use of the electric drive offer a more attractive ride to the passenger. The operator being relieved from the mechanics of gear-changing operations, is less fatigued at the end of the day's run. Public relations can be improved by use of the electric-drive bus, since driver fatigue is one of the usual causes of frayed nerves, snappy and discourteous retorts, and slovenly operating practices.

One advantage of the electric drive that is seldom considered is the decrease in "gassing" effected by eliminating overdrive of the engine during deceleration. One of the greatest single sources of complaint in bus operation, both from passengers and residents along the bus route, is the obnoxious exhaust gases discharged by the engine. This problem has attained proportions that justify consideration of the decrease in volume and change in characteristics of the exhaust gases discharged by the engine of the gas-electric bus due to its freewheeling action during declerating periods. Evaluation of these advantages accruing from use of the electric drive is obviously impractical, but its is believed that some weight should be given to the inherent "sales appeal" of the electric drive in any analysis of the advantages of that type vehicle.

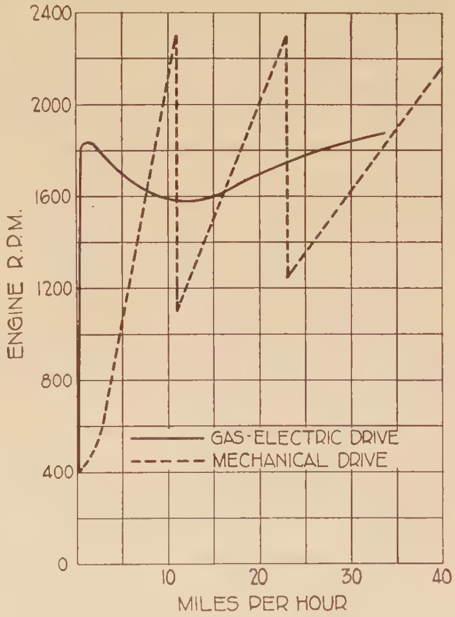
Operating expense is an all-inclusive factor that can be subdivided to minute detail. The major components of operating expense that are appreciably affected by the type drive utilized, include depreciation charge per vehicle, platform wages, gasoline or fuel cost, and maintenance expense. These factors can be estimated to some degree on the basis of known performance for each type bus.

Depreciation charges are a function of the difference in initial cost of the two types of vehicles and their probable economic life. Additional cost for the electric drive will vary, but can be assumed to be approximately ten per cent of the cost for a 35- or 40-passenger bus. Since depreciation charges will normally range from 2.5 to 3.5 cents per mile, use of the electric drive will increase the direct operating expense from 0.25 to 0.35 cents per mile, if we assume equal mileage life for the gas-electric and mechanical-drive busses. However, experience of the Philadelphia Rapid Transit Company would indicate that use of the electric drive prolongs the useful life of the vehicle by decreasing rate of obsolescence and decreasing physical deterioration of the vehicle. Evaluation of the potential increase in useful life of the electric-drive bus is a matter of individual opinion and judgment. It may be considered that the actual increase in depreciation charges incurred by use of the electric drive will vary from nothing to a maximum of 0.35 cents per mile, depending upon specific operating conditions and individual judgment.

The claims and counterclaims regarding effect of electric drive on scheduled speed ability of the motor bus, have tended to obscure the facts behind the smoke screen of controversy. The comparative acceleration characteristics of two identical vehicles, one electric drive, the other mechanical drive, were shown graphically, figure 1. These tests would indicate that there is a negligible difference between the probable scheduled speed abilities of the two vehicles. However, actual tests operated to measure scheduled speed ability, shown in figure 3, indicated that there is a definite and appreciable difference in scheduled speed operated by the two busses. The electric-drive bus operated a faster scheduled speed, varying from 6.4 per cent at four stops per mile to 8.6 per cent at eight stops per mile. These conflicting results can be readily correlated by examination of the conditions under which the tests were operated. The electric-drive bus accelerates automatically, the driver merely depressing the accelerator pedal, and no skill or special technique is required to consistently attain maximum performance. The mechanical-drive bus, however, is accelerated successively through three or more gear ranges. Speed at which gear change is made, and rapidity of gear change affect the acceleration rate of the vehicle. During any acceleration test, the driver is under tension, gear change is made at optimum engine speed, with the minimum of time loss and performance attained is the maximum. During scheduled speed tests there is a natural letdown on the part of the driver, despite the fact that there still exists the necessity for changing gears under controlled conditions. It is apparent that in actual service, the mechanical-drive bus can only approach but never attain maximum performance. The gear-changing operation slows up, and engine speeds at which gear changes are made vary widely from the optimum values. The increased scheduled speeds, shown in figure 3, maintained by the electric-drive bus represent the minimum that could be expected in service. It is concluded that in frequent-stop service, the electric-drive bus could maintain a scheduled speed ten per cent faster than could be maintained by a mechanical-drive vehicle of identical design and construction.

Scheduled speed affects those items of operating expense that are proportionate to bus hours and number of busses operated, provided service frequency permits adjustment of schedules to maintain constant the number of bus miles operated. In short-headway heavy-traffic service, such adjustment is usually possible for any appreciable change in scheduled speed. Increased operating speed will, therefore, decrease in direct proportion, drivers' wages, bus depreciation charges, and certain fixed charges. These expenses will normally average not less than 11 cents per mile for heavy-traffic urban service. An increase in scheduled speed of ten per cent would therefore effect a decrease in direct operating expense of 1.1 cents per mile.

Figure 4. Engine speed during acceleration



Comparative fuel consumption for the electric-drive and mechanical-drive busses is shown graphically, figure 2. These fuel-consumption values were measured at maximum performance, to minimize operating variables, and are not indicative of the values that would be obtained in actual service, although comparison between the two types of busses should be valid. The miles per gallon of gasoline for the mechanical-drive bus were consistently higher than for the electric-drive vehicle, the increase for the mechanical-drive vehicle varying from 22.9 per cent at four stops per mile to 23.1 per cent at eight stops per mile It will be noted that the percentage increase is practically constant over the range of service conditions from four to eight stops per mile. It may be assumed that determination of comparative fuel consumption under known conditions of actual operation will be a measure of difference in fuel consumption for the two types of vehicle. These busses were operated for a period of two months in actual passenger service. Two groups of runs were selected having similar traffic characteristics, and the drivers assigned to these runs were instructed in operation of the test busses. To eliminate, in so far as possible, variables of operation, the busses were interchanged each week between the two groups of runs. At the end of the two months' period, the mechanical-drive bus averaged 4.27 miles per gallon of gasoline and the gas-electric bus averaged 3.50 miles per gallon of gasoline, an increase of 18.1 per cent in miles per gallon of gasoline for the mechanical-drive vehicle.

Difference in fuel consumption between the mechanical-drive and electric-drive busses was measured with standard design engine and standard engine adjustments. The engine design and adjustments are predicated upon requirements of the mechanical drive, which differ radically in many respects from the requirements of the electric drive. Comparison of the requirements for optimum engine performance with the electric drive and the mechanical drive can be determined to some degree by comparison of engine speed characteristics during acceleration of the mechanical- and electric-drive busses, as shown in figure 4. It is evident from this graph that engine speed during acceleration of the electric-drive bus, ranged from 1,600 to 1,800 rpm, whereas the engine speed during acceleration of the mechanical-drive bus ranged from 1,100 rpm to 2,350 rpm, neglecting initial engine accelerating period during which clutch slippage takes place. Since the engine is designed for mechanical drive, it develops maximum torque at 1,100 to 1,200 rpm, the point of maximum power demand during acceleration, and the torque falls off as engine speed increases. It is evident that an engine designed for electric drive, developing maximum torque at the operating speed range of 1,600 to 1,800, would operate more efficiently and result in decreased fuel consumption of the gas-electric bus. The engine is carbureted to perform over the entire operating range of engine speed of the mechanical-drive vehicle, and is equipped with a carburetor accelerating pump to insure pickup at low engine speed and heavy load. The electric-drive vehicle does not require this type of carburetion, and fuel economy can be attained by adjusting carburetion in the electric-drive bus to actual operating requirements. Test data have also indicated that the permissible maximum engine compression ratio that can be operated without detonation, using a given fuel, is substantially higher with the electric drive than with the mechanical drive, due to relatively constant speed operation and the elimination of low-speed operation at heavy load. It is believed that increased use of the electric drive will tend to focus attention on the inherent possibilities of improved economy to be derived from changes in engine design to meet the actual conditions under which the engine operates with the electric drive. Although the test data would indicate that use of the electric drive results in an increased fuel consumption of from 18 to 20 per cent, equivalent to from 0.5 to 0.8 cents per mile, it is concluded that these estimates represent the maximum probable increases in fuel operating expense. Development of an engine design properly adapted to requirements of the electric drive should decrease the differential in fuel expense to a fraction of the indicated value.

Differences in maintenance expense for the electric-drive and mechanical-drive busses can be approximated qualitatively by analysis of the characteristics of the two types of drive mechanisms. It has been shown, table I, that maintenance expense for electric-drive equipment operated by PRT during recent years has varied from 10 to 13 per cent of total maintenance costs. The electric-drive equipment operated is of obsolete design and it is considered that maintenance cost for modern commutating-field equipment would be substantially less than the costs experienced. It is believed that the expense for the electric equipment should not appreciably exceed expense for clutch and transmission equipment of modern busses with remote engine location. There are a number of characteristics of the electric drive that contribute to lowered maintenance costs. Elimination of the shock of clutch engagement tends to minimize wear on axle gearing and lessen the general wear and tear on the entire vehicle. Engine maintenance is definitely decreased due to relatively constant-speed operation and elimination of high engine speeds, as shown graphically, figure 4. In addition, the ability to measure readily engine performance, by rheostatic loading of the power generator at periodic inspection intervals, contributes materially to improved engine maintenance. Free-wheeling action with electric drive further lessens engine wear and tear by eliminating overdrive of the engine. It may be concluded that there is a definite probability of lessened maintenance expense with the electric drive.

There is one other important factor that should be considered in weighing the relative advantages and disadvantages of the electric drive. Although bus operation is a relatively new industry it will be confronted in the future with the problem of increasing age of its employees and the resultant impairment of the physical abilities of individual drivers.

The trend toward increased acceptance on the part of all industry of a social duty toward its employees necessitates adoption of every device that may prolong the useful working life of the employee. The characteristics of the electric drive, in minimizing required driver skill and in decreasing the physical effort necessary to efficiently control the vehicle, permit satisfactory operation of that type bus by individuals that could not operate comparable mechanical-drive busses under the same service conditions. This factor is of paramount importance to those companies that are faced with the problem of extensive substitution of the motor bus for the street car. Many of the displaced car operators can be trained to operate an electric-drive bus who are not capable of satisfactorily operating the mechanical-drive vehicle. Even this advantage of the electric drive has a dollars and cents value, since the alternative to continuing the employment of many of these employees is to retire them on a pension that must be paid from operating revenues.

The effect of operating electric-drive or mechanical-drive busses on operating expense may be summarized as in table II.

It has been stated that selection of the electric drive or the mechanical drive bus is fundamentally a question of economics. The problem was reduced to the solution of the following equation:

Net income per vehicle = total revenue − total expense

Table II

	Economies in Operating Expenses (Cents per Mile)	
	Electric Drive	Mechanical Drive
Depreciation charges		0.00 to 0.35
Increased scheduled speed	1.10	
Savings in fuel costs		0.50 to 0.80
Savings in maintenance expense	0.25 to 0.50	
Total	1.35 to 1.60	0.50 to 1.15

Attempt has been made to evaluate the differences between the two type vehicles in order that solutions to this equation might be developed. It is concluded that in frequent stop, heavy traffic urban service, the electric-drive bus will produce a higher net income than the mechanical-drive vehicle, since it has been credited with increased sales appeal, resulting in a higher total revenue, and decreased operating expense.

Modern City Transportation

E. J. McILRAITH

IN MOST cities there are enough automobiles to carry all of the citizens at one time. Yet, there is still a great need for public carriers as a part of city life, and this need increases relatively with increase in size of cities. People pay with great enthusiasm for modern automobiles because they satisfy a desire for new style, more power, greater comfort, and higher speed. Public transportation in its service must recognize these desires.

Life today is streamlined, air-conditioned, finger-tip controlled, and wrapped in striking play of colors and lights. A competing company offers radio harmonizing and another must put in automatic tuning. Then comes "no squint," "no stoop," "no squat." It is an era of dramatic selling.

Not even steel making remains the same. It is alloys we need now. Yet, sales increase because people spend their money for whims, and the whims of yesterday become, through advertising, the needs of today. Trade grows and the keen organization gets its share, while the old shop gets more and more dust and cobwebs.

Transportation has changed, but not fast enough through the last generation. Political control fastened itself upon the street railways and steam railways. Now the other industries have their share of government control, and how they like it. We have grown used to it.

The successive blows of high costs due to the war, automobile competition, the depression, have kept many transportation companies without reasonable earnings for 20 years. Credit has been low, and there has been no sound modernizing plan available to bring back business or build up new lines of trade.

But the long-delayed modernization is now definitely in evidence. The correct solution is not fully understood or established, but experience is molding opinion. A great difficulty is the fact that too many of those who influence transportation are outside of the active management, and seek to find a standard solution applicable everywhere. Even among the operators of transportation systems one finds many expressing fixed opinions as if they were definite and unquestioned axioms.

We hear: Street cars are doomed—two-man car operation is silly—busses are the only solution—small busses are the perfect answer—trolley busses give best service at lowest cost—elevated railways are out.

Some individuals in prominent places believe firmly in the absolute accuracy of one or more of these statements. Each of these statements has definite adherents who are enthusiastically willing to argue for their beliefs, and to spend money based on those beliefs. Actually no one of them is correct in all circumstances, but each of them is true for certain operations, or for certain cities, or for certain circumstances. The great trouble is lack of analysis to determine the different solutions that are needed to give correct answers for the different situations that exist, and to provide the best service with the best operation, and the maximum net return at a reasonable rate of fare. There is no single unit that should be universally used, even in a single city except, perhaps, in cities of very small size.

The transportation industry like any other needs careful thinking and planning, careful analysis and application of sound principles. One doesn't build the same standard factory with an unvarying type of machine tools for a fixed number of workmen to manufacture shoes in one place and containers in another; nor would the same factory be built to manufacture shoes in Chicago as for a factory in Augusta, Georgia. Building a factory or building a transportation system calls for painstaking analysis of the market, the source of supply, the costs of materials, the wage rate, the type of machine tools, the layout of the plant, the operating and working conditions, the trend of public opinion toward the product, the possibilities of molding that opinion, and the probability of producing an adequate net return. Each of these problems has its influence on the success of the whole project.

The final answer that determines the success of an undertaking is the size of the net return after making allowance for the ability to hold the customers by maintaining the quality and price of output. One should not plan for a character of transportation service or kind of unit to be used in giving that service unless it best fits into the production of greater net earnings with satisfaction to the customers. A system should be built around these two objectives, using the best available tools and equipment for each of the many varieties of service within the community served.

Over the years since electric cars have been used, there has been continued progress; better trucks, motors, controls, brakes, doors, bodies, modernized lines but cars were made to last so long that many of the cars you rode on as boys are still with us. Only a pitifully small number of new cars were built each year. That is not real progress.

Ten years ago these facts were recognized and the desire for change finally resulted in the formation of the conference of the presidents of the larger transportation companies and representatives of equipment manufacturers. This conference gave the pressure that comes from large purchasing power to the designing and creation of a truly adequate modern car of two types, for one-man operation and for two-man operation.

Those cars are at last realities operating in several cities and demonstrating definitely that a street car can also be

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thoroughly modernized. The 1937 model car is speedy, sleek, quiet, attractive, and even as modern in appearance as the best bus and much more comfortable to ride. The next models will be better yet.

The new car has excited public interest as an innovation, has attracted many new riders and has gained for the railways new confidence in sound thinking to build a balanced, competent system, using adequate equipment for each transporation need.

What are the transportation needs?

Twenty-five years ago the only public carrier was still thought to be a street car on rails. Then came busses, first as unwieldly, awkard looking, as the early automobiles were, but improving steadily and developing through the years, even as automobiles have developed. Today the modernized bus has reasonable speed, power, comfort and has cleared most of its principal handicaps, except those of heating, lighting, ventilation, fumes of exhaust, and smoothness on uneven pavements.

As bus manufacture became more competent, trolley busses of an efficient type and of adequate performance were developed. Now we have an equally quiet, equally modernized street car for either one-man or two-man operation and surface units run the entire range from private automobiles to small busses to the largest bus, or trolley bus conveniently usable on city streets, into the rail vehicles for lines of heavy density of travel, all running speedily, quietly, smoothly, comfortably.

A full discussion of the relative merits and proper use of these units in a short paper is quite out of the question, but a brief reference to their relative positions is necessary. The principal reason for variety of unit is due to the difference in costs of maintenance, operation, and the various fixed charges to be met.

One cannot depend safely upon general figures on the relative cost per mile of operating street cars, busses or trolley busses, although that is what many managements seek to do, attempting to use approximate estimate as a measuring stick in determining the relative place of each of these types of vehicle. There is no uniform measure that can be correctly used as a generality even for a given city with a single organization and a single scale of wages, working conditions, and costs of material. One must study the cost of each single line and compare the analysis of several types of lines as costs would be for each of these several types of vehicles available to make clear the reason for this statement. The relative importance of operator's wages, milage, costs of maintenance and operation, and fixed charges such as interest on investment, depreciation, insurance, taxes, licenses, and city imposts, vary widely in their effect, dependent upon the characteristics of the operation of the street or line in question.

Unless one has made intimate analysis of proper scheduling of an operation and has found that waste in scheduling is so easily glossed over and ignored, he will not be aware of the significance of intimate study. Very few people understand the possibilities of careful schedule-making, and few schedule departments experience from management intensive understanding, supervision and pressure toward correct analysis and technique.

A few specific illustrations of relative total costs may indicate the need for applying careful, complete analysis to single lines before reaching conclusions as to size of unit or type of operation.

There are three lines in Chicago of nearly the same length but somewhat different riding characteristics. Number 1 carries 53,000 people per day, number 2 60,000, number 3 44,000. Careful detailed analysis of all the factors affecting operation, costs, and investments for each of the various types of operation—two-man cars, one-man cars, trolley busses and gasoline busses—shows that number 1 line would be best served by one-man cars, saving $30,000 per year over the next best type of operation. Number 2 would have the best net return by the use of two-man cars, saving about $25,000 more than by any other method. Number 3 line having somewhat lighter travel and different distribution is best served by trolley busses and these would be best by about $50,000.

By general measures of classification these three lines are alike and directly comparable. It would be easy to create the conviction that the three routes should be treated alike, yet, the net return to the company can be greatly improved by individual decisions and careful application of correct equipment.

The differences are created by the use of the lines by the passengers; that is, the relative intensity of the rush hour as compared to the nonrush period, the relative number in rush hour and nonrush using each of the two directions of travel, the length of ride of the passengers on the line, the zones in which they ride and the number of times the load changes on each trip.

Further, to demonstrate relative costs on one of these lines, index figures for the various types of units are:

Two-man car	118
One-man car	111
40-Passenger gas bus	108
30-Passenger gas bus	114
40-Passenger trolley bus	104

An even more striking illustration can be given by comparing two routes of exactly the same length. One, now a trolley bus line, carries about 19,000,000 passengers per year; the other is a one-man car line carrying 17,000,000 passengers. The average load per car or bus in rush hours in the rush direction is almost exactly the same for the two lines but because of the variations in such factors previously mentioned the total operators' hours paid for on the trolley bus line is 56 per cent higher than on the one-man car line.

Further analysis of the costs of giving gasoline bus service with different sizes of gasoline busses indicates again that general conclusions are likely to result in errors. One line using seven 30-seat busses could be operated with ten 20-seat busses of the same quality and general appearance, except for size, at a saving of around $7,000 per year, and with a reduced investment in busses from $63,000 for the 30-seat bus to $45,000 for the 20-seat bus. A saving of $7,000 with a reduction of nearly 30 per cent in investment is a very substantial accomplishment on so small a line, but the ordinary operating man would be likely to suggest a 30-seat bus if he looked at the line's operation somewhat superficially or without the careful analysis of the complete details of costs.

On another line using at present ten 30-passenger busses the total cost would be $4,000 more per year if smaller busses were substituted, but the investment would be lower for the 20-passenger bus. In each of these cases one is balancing operators' wages, which are naturally higher with the smaller bus, against costs of operation, maintenance and fixed charges, which are likely to be lower on many of the light lines for the smaller bus.

In most any system of transportation prevailing today in cities there are certain lines built many years ago when only street cars appeared to be serviceable for city service, and which have continued to operate with street cars where a substitution could readily be made at a saving by using trolley busses or gasoline busses as the circumstances would indicate. These two newer types of vehicles are better adapted to certain kinds of operation with lighter densities of travel, and should be a part of a modernized system for those lines on which they are appropriate. No one kind of equipment is adequate for best results in all types of service, and the production of net revenue. Rule-of-thumb methods of deciding upon the type of equipment can bring wrong answers.

Of course, another source of error comes from the use of old figures of costs of operation. New methods of maintenance and newer, better equipment are constantly being introduced in gasoline driven busses of all sizes, in trolley busses, and in street cars. The relative comparisons are an ever changing relation and, just as in all business ventures, transportation management needs to be alert in analysis, study, and in modernization.

The new street car generally known as the PCC, or Presidents' Conference Committee Design, has now been in use for more than a year in a number of cities. In most cities it is used as a one-man car; in Chicago only as a two-man car. But the Chicago car is larger in size with different arrangements of doors to make it adaptable for the carrying of larger loads. This car has distinct accomplishments that make it a completely different street car than has been available. The rate of acceleration is not greater than that of some of the best cars previously used, but is very much smoother and more uniform. Jerks are possible only when the motorman must throw off his control while the car is still accelerating at a rather high rate and must immediately put on his brake to avoid an accident. It is, of course, impossible to make such emergency stops without disturbing standing passengers. This is true in any type of vehicle equipped with efficient brakes.

The brake on the new car is a great improvement because braking is not dependent upon wheel adhesion. The combination of dynamic braking with air braking and a battery-operated track brake permits a quicker stop than is possible with an automobile, not withstanding the condition of the rail. Of course, the rate of braking ought to be selected as one that the passengers can tolerate when standing and holding to a support. But since the motorman knows that he is no longer dependent solely on rail adhesion, he may run closer to traffic, and at much higher speeds so that he may hold his place in the street.

The only way in which greater speed can be developed for a vehicle of this sort is by giving the operator complete assurance that he has a thoroughly dependable braking system that will operate at least as rapidly as that of any other vehicles on the street. The success of gaining speed in operation of these cars, then, has been made possible not primarily because of change in accelerating rates, but also because of improved braking.

The new car also has a much better heating and ventilating system, and uses the heat generated in accelerating and in decelerating by dynamic braking for heating the car. This practically eliminates the use of any other electrical heating, and so cuts the cost materially.

The modernized design of equipment in unit assembly has greatly reduced problems of maintenance and has cut costs in both maintenance and manufacture. The weight of the whole car has been materially reduced by better design, and modernized methods of manufacture, made possible by many companies purchasing from similar specifications, has reduced greatly the manufacturing cost and, therefore, the purchasing price.

However, the outstanding accomplishment is the reduction of noise to a level in keeping with that for busses or automobiles. Without noise reduction the new street cars would be quite incomplete, in spite of the important advantages they have for many lines in all large cities. With the present demonstration of a very quiet street car which can, no doubt, be even further improved in later models, the greatest handicap or source of annoyance has been definitely eliminated.

In the Chicago cars, hand control of the motor circuits and of the brakes is used. The motorman operates the controller with his left hand by a lever that moves vertically through an angle of 22 degrees, the position determining the rate of automatic acceleration chosen. With the right hand he operates the brakes with another lever, also in a vertical plan through an angle of approximately 60 degrees. Here the position determines the automatic rate of deceleration.

This is not quite all the story of the braking controller, because the three forms of braking are not ordinarily all effective at the same time, and the track brakes do not begin to function unless the control handle is moved beyond the middle of its stroke.

The point I wish to make is that we have kept hand control of the movement of the vehicle, while all other properties have gone wholly to foot control in both starting and stopping the car. The principal reason for retaining hand control is that in the operation of a street car no steering is required, so that while the car is running the operator on a two-man car has nothing whatever that he needs to do with his hands, if acceleration and braking are put on foot pedals. Now it isn't good psychology to leave a man at an important job that calls for a high degree of concentration on the smoothness and safety of his operation with his hands idle. One's thinking is too much tied up with what the hands are doing. Hands will not stay idle, and if the operator when operating a car begins to do other things with his hands that take away his attention from safety and smoothness of the car, then the job is being poorly done.

Hand operation with proper kinds of movements can be much more accurate than can foot operation, and due to the flexibility of one's hands, wrists, arms, and body one may make levers move accurately up and down in a vertical direction even though the body is not in a fixed position in a seat.

Other problems remain yet to be settled. All of the new cars in use are front-entrance, center-exit cars. In Chicago a rear exit was also added. But the passengers still tend to concentrate in the front half of the car. It is quite likely that this is inescapable and that in two-man operation it is necessary to have rear-entrance, center-exit, and front-exit, in order that the passengers may be permitted to move in the direction that is psychologically sound, and in which they are most easily trained, instead of trying to force the passengers to go back to alight at points farthest from the crosswalk. The street intersection seems to be their main objective. While passengers are waiting for a car they will move back toward a boarding point where the rear end will be because they are not wasting time in so doing. When they get off they wish to be at the nearest possible point to the street intersection. It seems that this is too strong a tendency to overcome, and that reversal of the present movement for two-man cars will not only accomplish better distribution of the loads, but will also tend to reduce accidents within the car, because the passenger will be facing in a better direction for bracing himself against acceleration or deceleration, and in one to which he has been accustomed over a long period of years of training.

However, the car has been a notable success, and undoubtedly large numbers will be built and used in many cities in modernization now underway. It seems quite important that electrical operation be retained in cities. Certainly the air in the streets is cleaner and better without the annoying fumes of gasoline driven units. Fortunately, on heavier lines electrical vehicles, either street cars or trolley busses, are more economical and perhaps it is much better to have transportation systems largely dependent on central station energy than to be dependent on gasoline or oil, which may become in a few years relatively more difficult to obtain and more costly in use. The source of gasoline is not unlimited. Of course, if Diesel engines can ultimately be developed to be utilized to advantage, the increased use of Diesel oil will also cause a rise in price, but Diesel engines in city service need to be equipped as Diesel-electric type, which produces added complications.

But electrically controlled vehicles served by central stations would have marked advantages from the standpoint of fumes, better heating, lighting and ventilation, lessened noise, greater dependability in power source, and they may also be made larger. Street cars and trolley busses are permitted to be wider than gasoline driven busses because they cannot get away from their city streets into state highways, and when wider may have wider aisles, wider seats, wider doors, and generally better transportation convenience for lines of frequent interchange of passengers.

The conclusion that should be reached from this discussion is that a process of change is going on. Modernization and improvement is vitally necessary, but accurate thinking indicates the need for care in making decisions. Sound transportation planning will utilize all the best ideas and will develop plans that will permit continuing modernization.

Thyratron Reactor Lighting Control

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Synopsis: The introduction of electron tubes and power saturable reactors for the control of theater and mobile lighting has made possible the design and construction of lighting control equipment of greater efficiency and flexibility than was possible with the older methods of control. This paper describes some of the new equipment, systems, and practices.

Several control systems for the pilot controller, the individual, and master units are described and illustrated. The basis for the intensity scale for the control units in the pilot controller is given.

Introduction

IN A PREVIOUS paper,[1] an electron-tube saturable-reactor circuit was described which has proved to be a basic element in the development of a system of theater-lighting control adaptable to a wide range of applications. In applying this circuit it has been possible not only to enlarge former systems of control, but also to develop new and more flexible systems which have proved to be of great practical value. It is the object of this paper to explain some of these systems and the characteristics of some of the component parts.

The theater-lighting control equipment here described is made up of two basic parts, reactor groups and a pilot controller. The reactor groups consist of thyratron-tube panels, distribution panels, saturable reactors, and booster transformers, which regulate the amount of power supplied to the lamp circuits. These reactor groups can be located in any remote place, but are usually situated at a load center. The pilot controller is constructed in the form of a console or vertical panel from which the operator has control of all lighting circuits and is located in front of or at the side of the stage in order that the operator may see the lighting effects which are being produced.

Control Units

The pilot controller consists of individual intensity-control units, master intensity-control units, etc. The number of each used and their arrangement depends upon the control system employed and the number of lighting circuits. In each of these units there is a small lever or knob moving on a calibrated scale for controlling the light circuit intensity.

An outstanding advantage of the thyratron-reactor control over resistance dimmers is the fact that the calibration of this intensity scale serves two purposes:

1. It acts as an index or guide for resetting the lighting circuit and
2. It is a true indication of the percentage of light intensity.

This latter condition is based on an experimental determination[2] of a series of reflecting surfaces which represent a series of equal differences in brightness sensation for the average observer. The intensity scales are arbitrarily marked from zero to ten and correspond to equal divisions of brightness sensation, i.e., zero on the intensity scale indicates no light, five indicates 50 per cent brightness, and ten indicates 100 per cent brightness or maximum light output. Plotting light output in per cent lumens against the intensity scale gives the ideal curve (figure 1, curve *A*). Converting per cent lumens to volts for Mazda *C* lamps[3] provides a convenient basis of comparison for determining how closely control units give results approaching the ideal curve (figure 1, curve *B*).

By referring to illumination levels on a percentage basis, a new terminology is made available to the lighting director since the calibration of the intensity scales is in units which are proportional to the brightness sensation of the human eye.

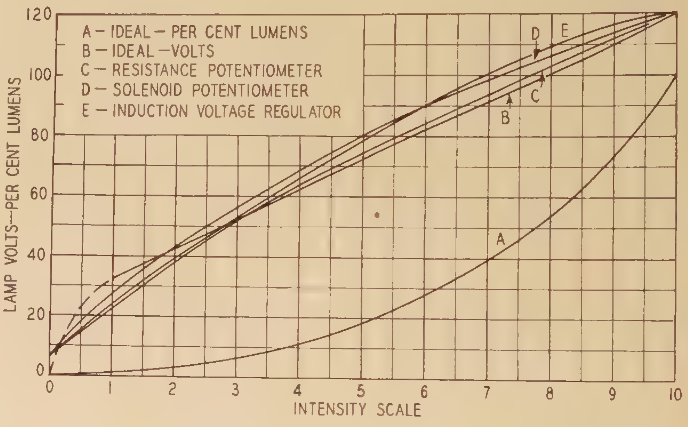

Figure 1. **Ideal and actual characteristic curves of individual control units**

A—Ideal, per cent lumens
B—Ideal, volts
C—Resistance potentiometer
D—Solenoid potentiometer
E—Induction voltage regulator

Individual Intensity-Control Units

1. *Resistance Potentiometer.* A resistance potentiometer was used as the intensity control unit in the description of the theater lighting control circuit previously referred to. The current drawn by this circuit from the intensity control unit is about three milliamperes and hence a resistance potentiometer of small physical size and having a resistance of several thousand ohms can be

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[1] For all numbered references, see list at end of paper.

used. The potentiometer is usually mounted with the shaft perpendicular to the face of the unit so that the control knob is turned to control the lamp circuit intensity. Uniform wire-wound potentiometers are usually used, and the intensity scale calibrated to correspond as nearly as possible to the ideal characteristic (figure 1, curve *C*).

2. *Solenoid Potentiometer.*[4] Figure 2*A* illustrates a typical control unit using a solenoid potentiometer. Control of the lamp intensity is effected as follows:

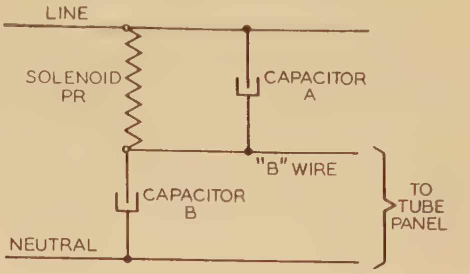
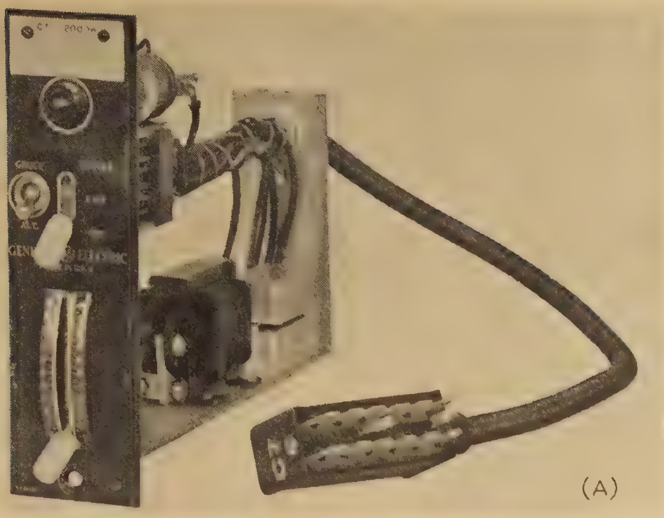


Figure 3. Connections of solenoid potentiometer

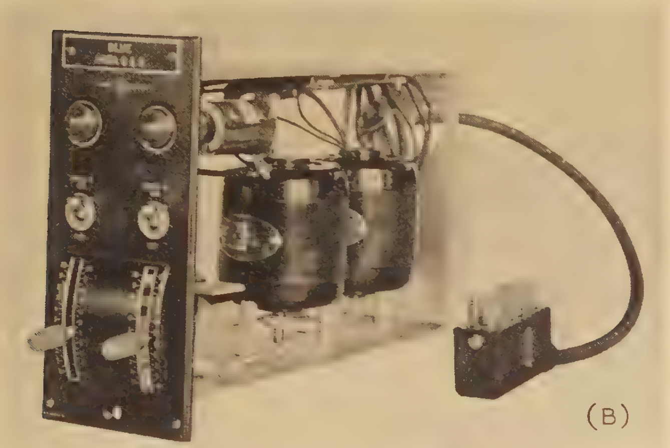
Referring to figure 3, change of voltage between the *B* wire and neutral is obtained through the resonant rise and fall of voltage across capacitor *B* as the inductance of solenoid *PR* is varied from a low to a high value. That is, solenoid *PR* goes from series resonance with capacitor *B* into parallel resonance with capacitor *A* as the inductance of *PR* is increased. From the above description, it is evident that this intensity control consists of a regulating scheme similar to an ordinary resistance potentiometer but employing solenoid *PR*, capacitor *A*, and series capacitor *B* to control the voltage magnitude existing between the *B* wire and the neutral through the variation of the inductance of *PR* caused by the change in position of an iron core rather than by the change in position of a sliding contact. The intensity scale is uniform because the proper selection of solenoid coil and capacitors gives an intensity calibration (figure 1, curve *D*) which closely approaches the ideal characteristic.

3. *Induction Voltage Regulator.* A control unit using induction voltage regulators is shown in figure 2*B*.

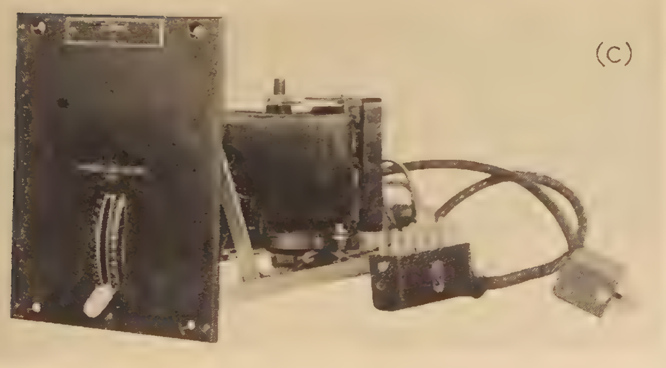
The induction voltage regulator consists of a stator winding and a rotor winding. The stator winding, when connected to an a-c source, induces a voltage in the rotor winding depending upon the relative positions of the stator and rotor. In order to use an induction voltage regulator as an individual intensity control unit, it must be of small size. However, it has been impractical to build a regulator whose maximum rotor voltage is as high as that required by the tube unit. Therefore, to increase this voltage a transformer is connected between the rotor and the tube unit. The induction voltage regulator generally is not used singly, but in conjunction with similar regulators in preset control systems. As the curve of output voltage versus angular position of the rotor is sinusoidal, a uniform intensity scale can be used because the proper selection of mechanical linkage gives an intensity calibration (figure 1, curve *E*) which closely approximates the ideal characteristic.



A—Solenoid potentiometer type



B—Induction voltage regulator type



C—Master (above) *D*—Scene fader (below)

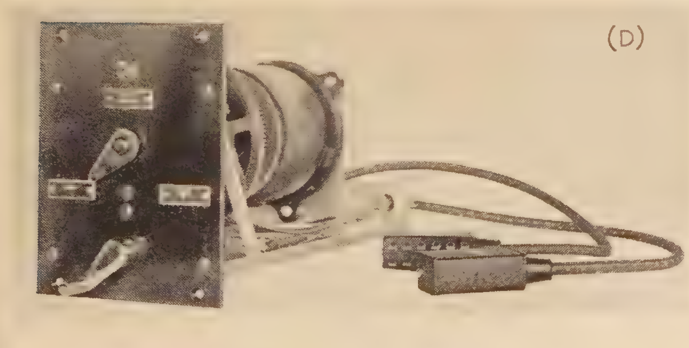


Figure 2. Control units

MASTER INTENSITY-CONTROL UNIT

The master intensity-control unit is used to control a group of individual units or other master units. It usually consists of a toroidally wound adjustable autotransformer so arranged that power may be tapped from any turn of the winding. Any voltage from zero to full value may be obtained from this device with but small increments of voltage between steps. One form of a master in which the adjustable auto transformer is operated by a rack and pinion is shown in figure 2*C*.

SCENE-FADER CONTROL UNIT

The scene-fader control unit used in preset systems makes it possible for the operator to fade the light circuit intensities of one scene into those of another. It usually consists of an adjustable autotransformer similar to that used in the master unit, but mounted with shaft perpendicular to the panel (figure 2*D*). Instead of the lever a small crank is used through reducing gears to slowly adjust the transformer.

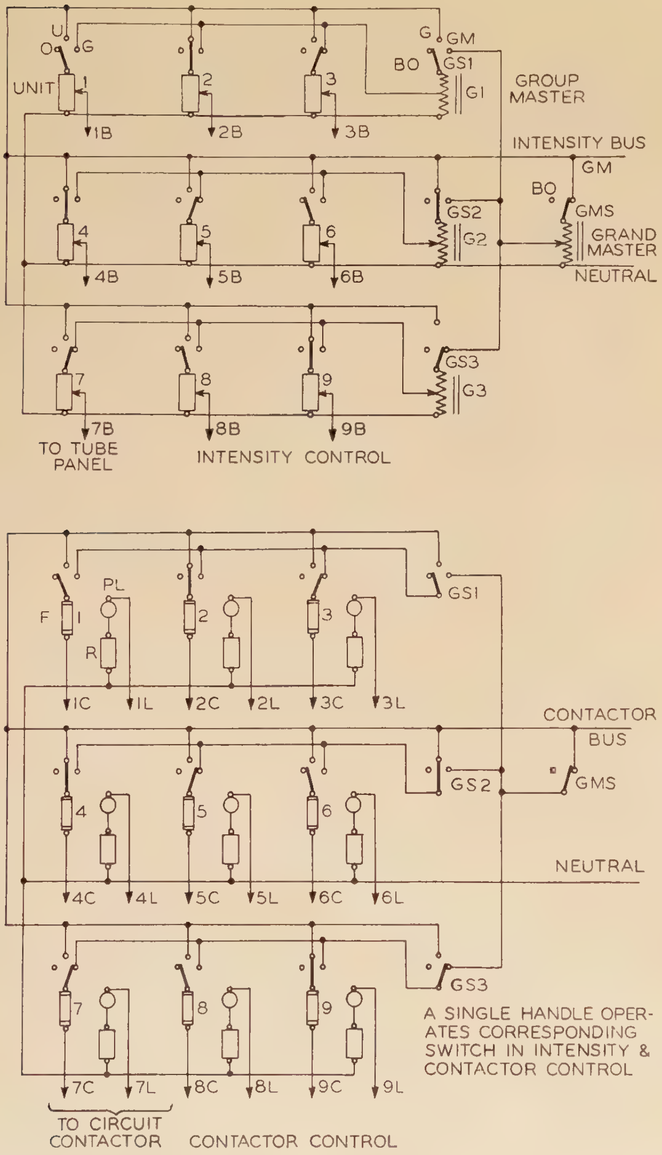


Figure 4. Schematic of pilot controller—typical rehearsal system

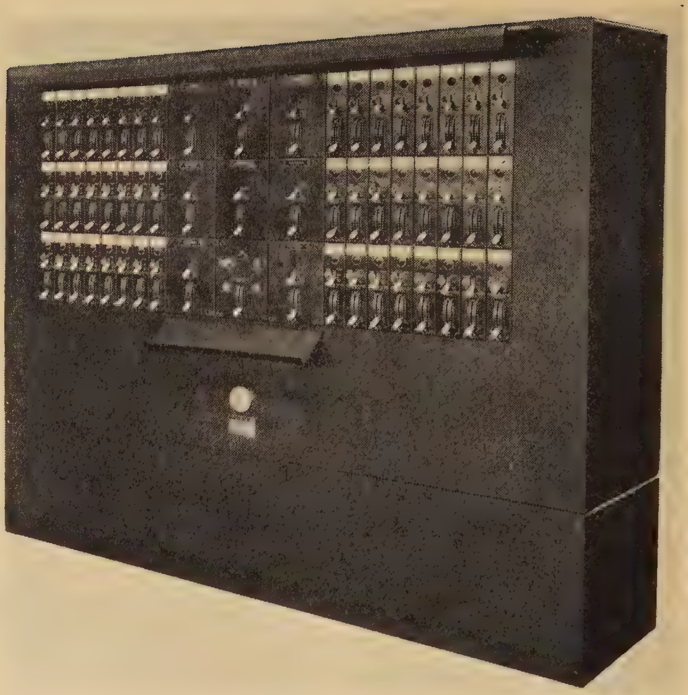


Figure 5. Pilot controller using rehearsal system

Systems

As pointed out above, the pilot controllers consist of individual units, master units, switches, etc. In general, the systems of control for the pilot controllers are classified as rehearsal, preset, rehearsal and preset, or modifications of these.

REHEARSAL SYSTEM

In the rehearsal system, individual units are arranged in groups and may be controlled from a group (or color) master, and these masters may in turn be controlled from a grand master. Figure 4 shows, schematically, a typical rehearsal system.

A contactor control may be included in the system, which provides a switching arrangement for circuit contactors so that, for example, all circuits connected to a group master may be turned off quickly and simultaneously by putting the three-position switch in the group master in the "blackout" position. The pilot light on the individual unit indicates when the circuit contactor is closed. In figure 4 the contactor control is shown separate from the intensity control for clarity, whereas actually the functions of the two are combined.

The individual units, illustrated as potentiometers, may be connected to the "off," "intensity line bus," or a "group master intensity bus" by their three position switches. The customary designations for these three positions are "off," "unit," and "group master," respectively. In figure 4, circuit 6 is in the "off" position, circuit 4 is in the "unit" position, and circuit 5 is in the

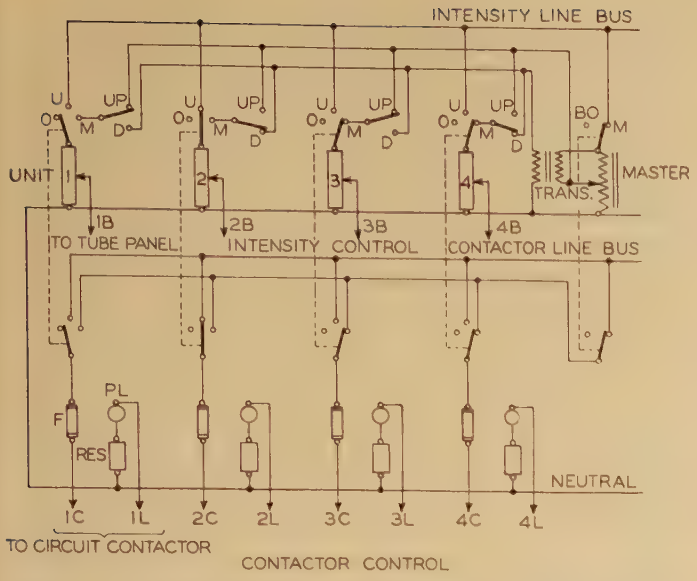


Figure 6. Schematic of pilot controller—rehearsal system with cross control between individual units and master unit

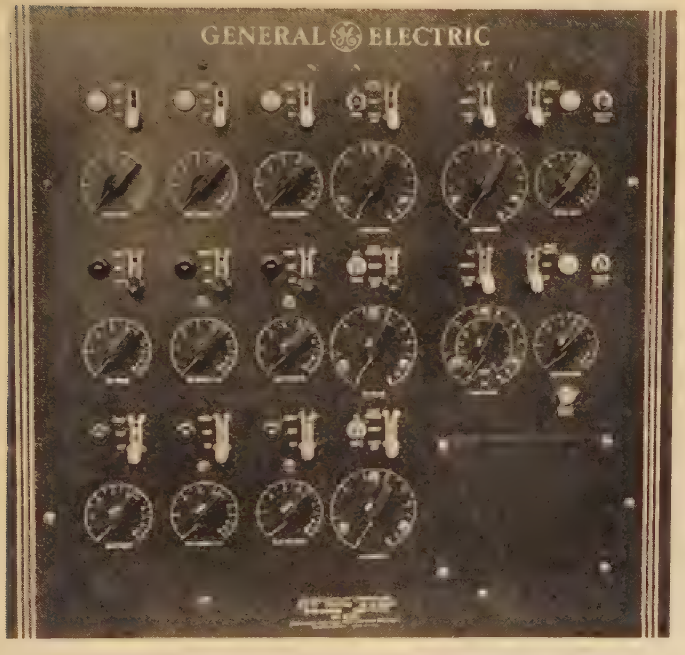


Figure 7. Pilot controller—Rehearsal system with cross control between color masters and stage master

"group master" position. As the lamp intensity of each circuit depends upon the voltage between the *B* wire and neutral *N* for the respective circuits, the lamp intensity for circuit 6 will be zero, for circuit 4 will depend upon the setting for that individual unit, and for circuit 5 will be proportional to the setting of that individual unit and group master 2. For example, if the individual unit and the group master are each set at one-half intensity position, the lamp intensity will be one-fourth. If units 4, 5, and 6 are connected to the group master and one is set at full intensity position, another at one-half, and the third at one-fourth, then as the master unit is increased from zero to full, the intensity of each circuit will increase in proportion, reaching full, one-half, and one-fourth, respectively, when the master reaches the full intensity position.

The group masters are connected to the grand master when their three-position switches are in the "master" position, to the line when the switches are in the "group" position, or off when the switches are in the "blackout" position. The lamp intensity of a lighting circuit, whose control unit is connected to the group master and the

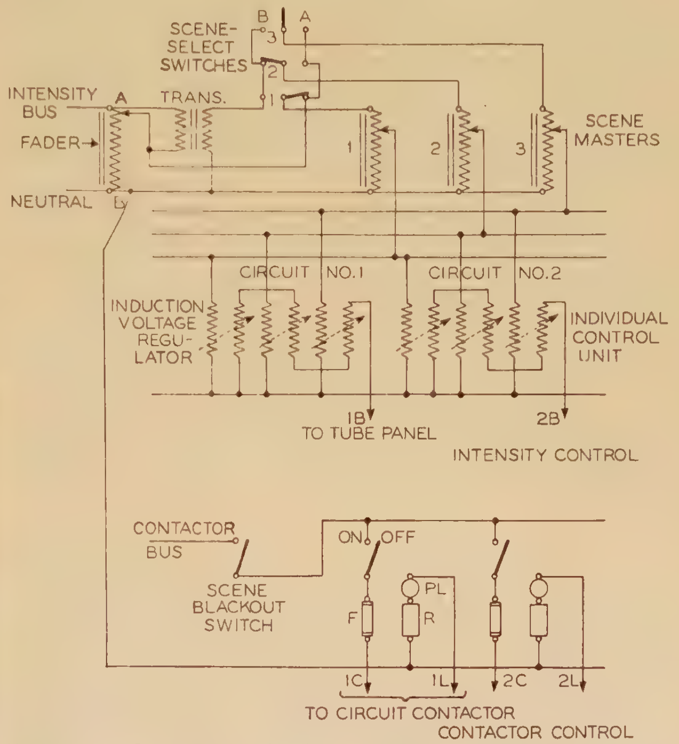


Figure 8. Schematic of pilot controller—three-scene preset system

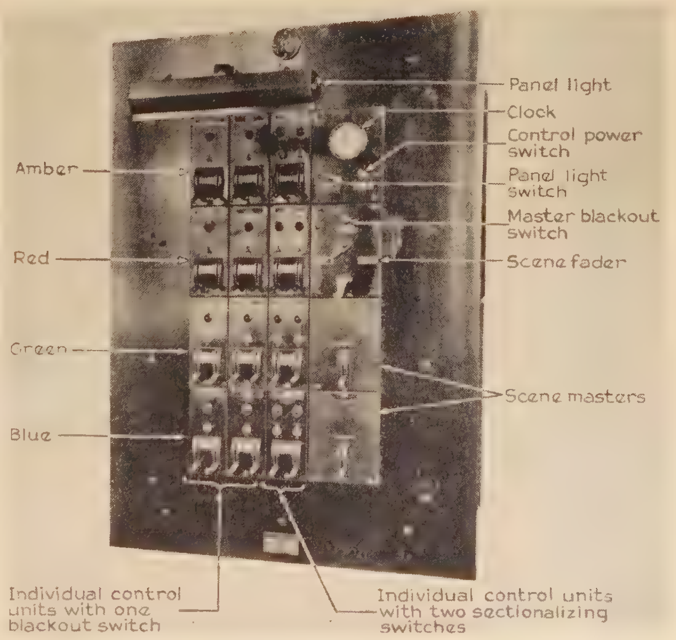


Figure 9. Pilot controller using two-scene preset system

group master connected to the grand master, will be proportional to the setting of the individual unit, the group master, and the grand master. For example, if the unit, group master, and the grand master each are set at half intensity, the lamp intensity of the lighting circuit will be $^1/_2 \times {}^1/_2 \times {}^1/_2 = {}^1/_8$. Units which are connected through the group masters to the grand master can be turned off by putting the two-position switch on the grand master in the "blackout" position.

The pilot controller shown in figure 5, installed at the University of Iowa, consists of a grand master, six group masters, and six groups of eight individual units, each of the solenoid potentiometer type, using a system similar to that just described, except that an alternate master is provided and two-position switches on the individual units select the group master or the alternate master.

A modification of the rehearsal system which increases the flexibility of a pilot controller is the addition of cross control between the individual units and the group masters, or between the group masters and the grand master. Figure 6 illustrates cross control between the individual units and the group master. A two-position switch on each unit enables a selection to be made so that as the intensity lever on the master is moved in one direction the intensity of some circuits increases while the intensity of other circuits decreases. This is accomplished by use of a transformer connected to the master as shown, so that as the voltage from the master increases the voltage from the transformer decreases.

The pilot controller shown in figure 7, installed at the Stetson High School, Philadelphia, consists of a house master with two individual units of the resistance potentiometer type, a stage master, three color masters, and three groups of three individual units each. Cross control is provided between the color masters and the stage master.

PRESET SYSTEM

In the preset system, the circuit intensities for a future scene can be set in advance. Transfer from the present scene to the following scene is made by closing the proper scene-select switch and turning the fader to the new position. The lamp intensities of the present scene fade uniformly into that of the following scene as the fader is turned. In this transfer the primaries of the voltage regulators[5] of the present scene are de-energized while the voltage regulators of the future scene are energized. The voltage from the secondary of the regulators depends upon the primary voltage and the angular position of the rotor with respect to the stator. For example, in figure 8 suppose circuit 1 is set at one-half intensity in the present scene (scene 1) and is to be full intensity in the next

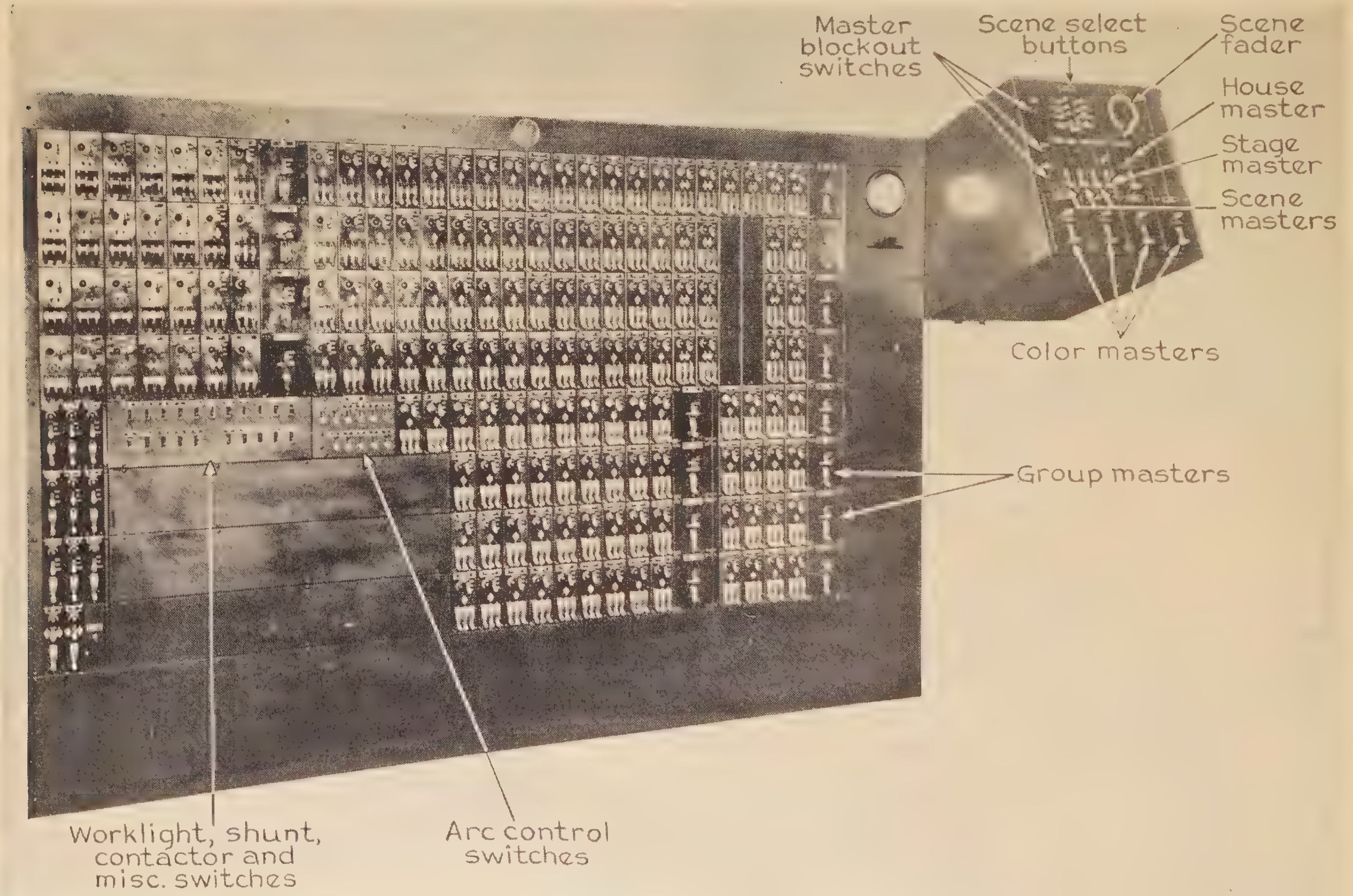


Figure 10. Pilot controller using rehearsal and three-scene preset system

scene (scene 2), and circuit 2 is at full intensity and is to be zero intensity in the next scene. The scene-select switches and fader are as shown, and it is seen that the primaries of the scene-1 regulators are energized and the other regulators are not energized. The scene-2 regulator for circuit 1 is placed in the full intensity position and the scene-2 regulator for circuit 2 is at the zero position. Then by turning the fader from *A* to *B* the voltage decreases on the primaries of the scene-1 regulators from maximum to zero, and at the same time increases the voltages on the primaries of the scene-2 regulators from zero to maximum. The lamp circuit intensity for circuit 1 has thus increased uniformly from one-half to full, and for circuit 2 has decreased from full to zero. All units of a given scene can be controlled by the scene master. For example, the scene-2 master can now be used to dim all units on scene 2.

The scene-select switches in figure 8 are not required if a preset system for only two scenes is used. In this case each individual unit has but two voltage regulators for intensity control. The scene-1 regulator stators are energized and the scene-2 regulators de-energized when the fader is turned to the scene-1 position. On turning the fader to the scene-2 position, scene-1 regulators are de-energized and scene-2 regulators are energized. Figure 9 shows the pilot controller installed at Maple Leaf Gardens, Toronto, Ont., Canada, which is of this two-scene preset type.

PRESET AND REHEARSAL SYSTEM

An extremely flexible control system is made by combining the rehearsal system and the preset system. Such a combination provides a single pilot controller having the advantages of both systems. A three-scene preset and rehearsal control system is used in the pilot controller (figure 10) for the stage lighting circuits at the Metropolitan Opera House. The scene fader, scene-select switches, scene masters, stage masters, and group masters are the same as in the previously described systems. Refer to figure 11. The individual control unit consists of three induction voltage regulators and a three-position switch. Each of the three positions of the switch represents three different connections of the individual control unit: (1) "unit," wherein the circuit intensity is controlled only from voltage regulator number 1; (2) "group," wherein the circuit intensity is controlled from voltage regulator number 1, the group master, or the stage master, as in a regular rehearsal system; and (3) "preset," wherein voltage regulators number 1, number 2, and number 3 are the intensity controls for scenes 1, 2, and 3, respectively.

Summary

Three types of individual intensity control units, a master intensity control unit, and a scene fader for use in theater-lighting pilot controllers have been described. A scientific basis for a rational marking of the intensity scales on the individual units has been given. Three basic systems of connections for pilot controllers and several modifications of these systems have been described. From the foregoing description of the various systems it may be seen that pilot controllers may be adapted to varying requirements for theater lighting control and furnish a wide variety of possibilities in the selection and production of lighting effects.

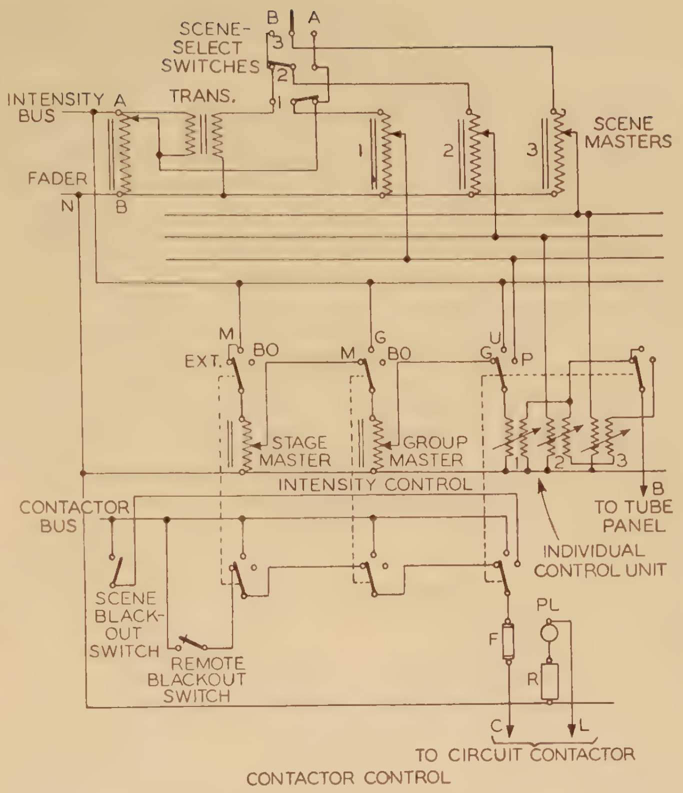


Figure 11. Schematic of pilot controller—rehearsal and three-scene preset system

Nomenclature—Schematic Diagrams

EXT—Extended control from remote blackout switch
F —Fuse in contactor coil circuit
GMS—Grand master switch
GS1 —Switch on group master number 1
PL —Pilot light
R —Resistor

CONTROL-UNIT SWITCH POSITIONS

BO —Black out
D —Down
G —Group master
GM —Grand master
M —Master
O —Off
P —Preset
U —Unit

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Thyratron Control of D-C Motors

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Synopsis: This paper describes the characteristics of new thyratron circuits which have been developed for the control of direct current motors. By means of these circuits it is possible to hold constant motor speed, constant armature voltage, or constant relative speed between two systems. It is also possible to hold constant either an alternating or direct current voltage which is dependent on the speed or position of the armature of a direct current motor.

Introduction

THE USE OF electron tubes in the industrial field has grown steadily for the last ten years. They have found their greatest application where other methods of control could not readily be used or were decidedly inferior. Speed control of d-c motors by means of thyratrons is in direct competition with those using rheostats, vibrating contacts, and other similar forms of field control. The thyratron has the advantage of high efficiency, full control, and quickness of response. The small control energy required, and the quickness of response greatly simplifies the design of precision control circuits and reduces the problem of hunting. A further advantage, in comparison to the rheostat control, is that it is not necessary to make step-by-step calculations of resistor values to obtain uniform control throughout the entire speed range. In general, the power component of thyratron control circuits is limited only by the maximum current to be controlled, and the range of control required. The first determines the size of tubes and power transformers and the second determines the magnitude of the anode voltage. In most applications, since 230 volt motors are used, the range of control is the same, and the only variable is the maximum current to be controlled.

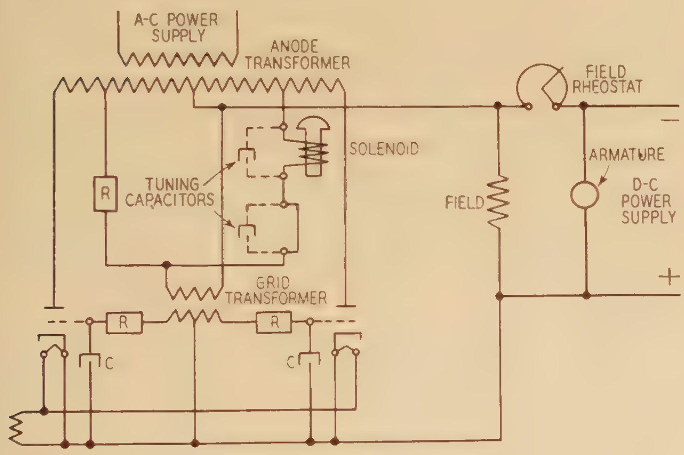

Figure 1. Thyratron field-control circuit with solenoid control

A number of thyratron circuits have been developed both for the control of a-c and of d-c motors. Some utilize feed-back systems to hold the speed constant, but in general, their main function is to provide a smooth adjustable control of the motor speed. There are, however, a large number of d-c motor applications where some type of feed-back system is necessary.

This paper describes some of these feed-back control circuits and their characteristics. Where new circuits were developed every effort has been made toward simplicity and to the use of the same fundamental elements. These circuits can be divided into mechanical feed-back and electrical feed-back systems. In mechanical feed-back systems such as wire reeling applications where the tension of the wire is held constant, the position of a solenoid is varied mechanically, such that the speed of the controlled motor will vary as the reel diameter changes. In electrical-feed-back systems a voltage or current is used as a reference to maintain constant tension or speed or to hold the speed of the controlled motor at some definite relationship with reference to the speed of another motor or system.

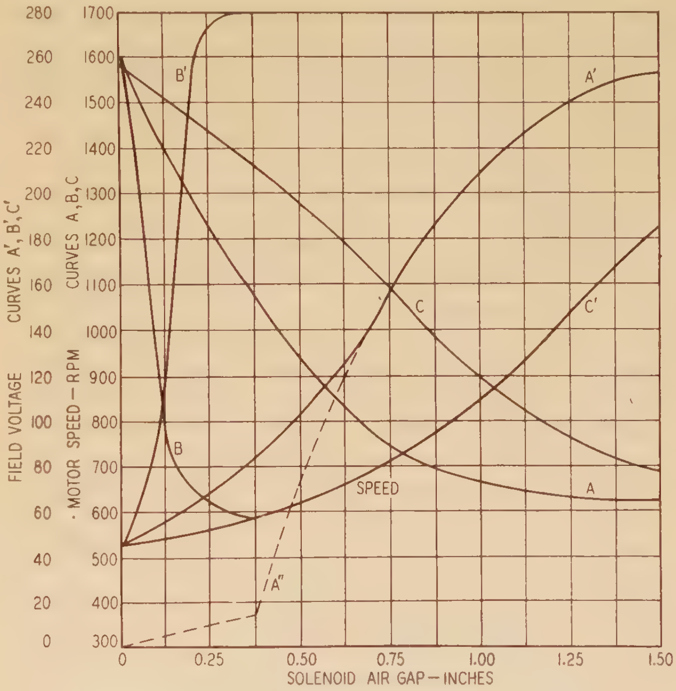

Figure 2. Motor-speed and field-voltage curves for figure 1

Data for this paper were taken on a shunt motor rated

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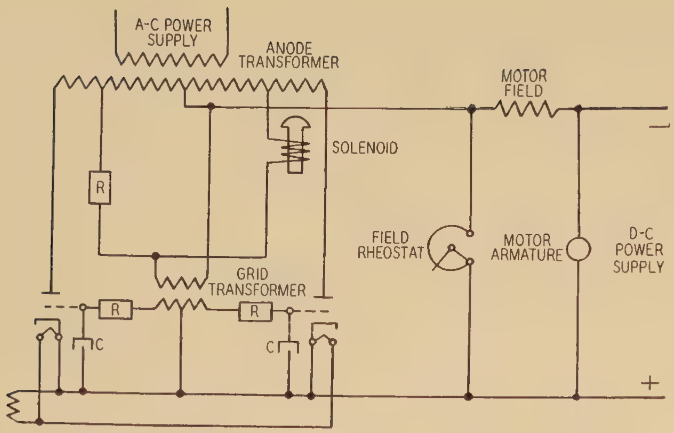


Figure 3. Thyratron field reducing control circuit with solenoid control

one and one-half horsepower, 230 volts, 500/1,500 rpm. In discussing the characteristics of these circuits it has been assumed that these data are typical for the control of any d-c motor. Actually, of course, the characteristics of motors vary, but it is believed that their differences are no greater than the variations caused by changes in the various circuit values.

Thyratron Power Circuit

In these feed-back circuits thyratrons are used as phase-controlled rectifiers for furnishing either the field excitation or the armature power. If the required speed range is narrow, field control is used and if wide or if time delay of the field circuit is objectionable, because of slowness of operation or increased tendency to hunt, armature control is used. In either case the voltage impressed on the motor is not continuous but has a large ripple component. The percentage ripple is still further increased by phase control.

The effect of this ripple voltage is to increase the losses in the motor circuits. When used for field excitation its effect usually can be neglected because of the smoothing effect of the field inductance. A test on a one and one half horsepower motor indicated that the ripple voltage increased the field heating by less than two degrees centigrade.

When used for armature control this smoothing effect is not present and in addition current cannot flow from the thyratrons into the armature circuit until the impressed sinusoidal voltage becomes greater than the counter electromotive force. For this reason unless a smoothing reactor is used the armature current may consist of a series of impulses which may increase sparking of the commutator and cause an abnormal temperature rise in the commutator and particularly in the interpole windings. In some cases for small motors of one horsepower and less, when a biphase rectifier was used, it has been found more economical to use a larger motor rather than to add a smoothing reactor. Tests indicate that for the same load the motor should be approximately 25 to 35 per cent larger than that required if the ripple voltage was not present. The increased heating in the motor depends upon the percentage of ripple current, which in turn depends upon the reactance in the armature circuit, the number of phases in the rectifier circuit and the ripple voltage produced by phase control. The increased rise in temperature is illustrated by table I.

It will be noted that the greatest rise in temperature occurred in the interpole windings and was caused by increased core and copper losses. The field poles normally are not designed for the alternating flux produced by this ripple current.

Table I. Temperature Rise in Degrees Centigrade; $1^{1}/_{2}$-Horsepower 230-Volt 500/1,500-Rpm Motor

	With Direct Current Applied. 100 Per Cent Rated Armature Current	With Smoothing Reactor. 100 Per Cent Rated Armature Current (Average Amperes)	Without Smoothing Reactor. 75 Per Cent Rated Armature Current (Average Amperes)
Field windings	50	52.5	48
Interpole windings	40	42	38
Commutator	31	31.5	18

All readings were taken by thermometer immediately after the motor was stopped at end of test. Biphase type rectifier used for thyratron power circuit.

Even with a smoothing reactor the armature current may be discontinuous at light loads. As the load is increased a sudden change may occur in the armature voltage when the current changes to a continuous value. One reason for this change is that due to regulation in the anode transformer the critical grid voltage curve is no longer smooth, but has a discontinuity when the anode current stops. Therefore, unless the control-grid voltage crosses the critical grid voltage vertically, there will be an appar-

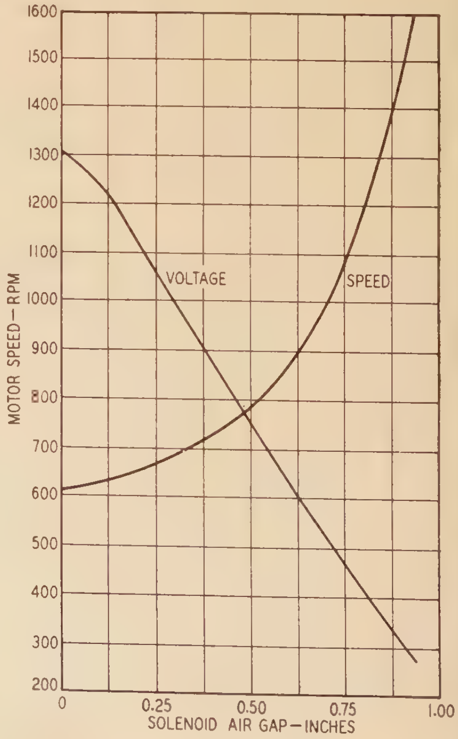
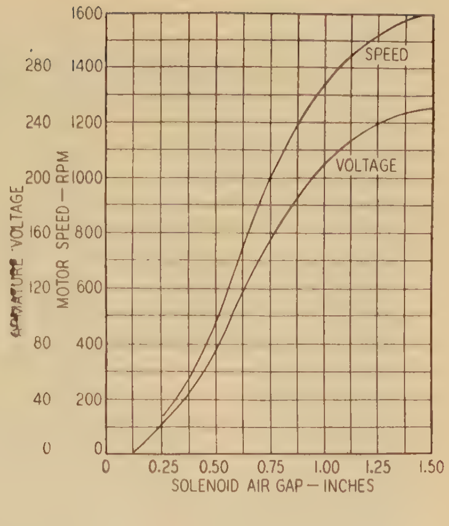


Figure 4. Motor-speed and field-voltage curves for figure 3

ent phase shift in the grid voltage which tends to suddenly increase the output voltage. By using a large inductance this discontinuity can be made to occur at such a low value of current that the control is not affected. Where it is impractical to use a large reactor there are two other methods which can be used to reduce the effect of this discontinuity to a negligible value. A resistor can be connected across the reactor or a phanotron tube can be connected across the output terminals of the rectifier circuit. In the first case the transition point is raised above the maximum load current value, without seriously increasing the heating in the motor, and in the second case the phanotron, because of its low effective resistance, increases the time constant to such a value that the discontinuity occurs at a very small value of current and has the effect of using a reactor of greater size.

Figure 6. Motor-speed and armature-voltage curves for figure 5



Control Circuit

Numerous methods have been developed for varying the apparent phase of the thyratron grid voltage. One method is to superimpose a variable d-c voltage on a fixed a-c voltage; another is to vary the phase of a peaked voltage, but the simplest method is to use a sinusoidal voltage of adjustable on variable phase. The superimposed control has the disadvantage, unless an amplifying tube is used, that the control voltage is so low that the variation in thyratron characteristics, caused either by changes in temperature or by usage, tends to limit their application or to have them discarded before their ultimate life was reached. With variable phase control the grid voltage can be made large enough to compensate for these variations.

A common method of obtaining phase control is to use a variable reactor in a resistance-reactance bridge circuit. The variable-reactor method of control has the advantage that contacts are not required. If a small saturable reactor is used for the variable-reactance element its reactance can be smoothly varied by changing the saturating current. For mechanical feed-back systems the ordinary solenoid is satisfactory for the variable-reactance element.

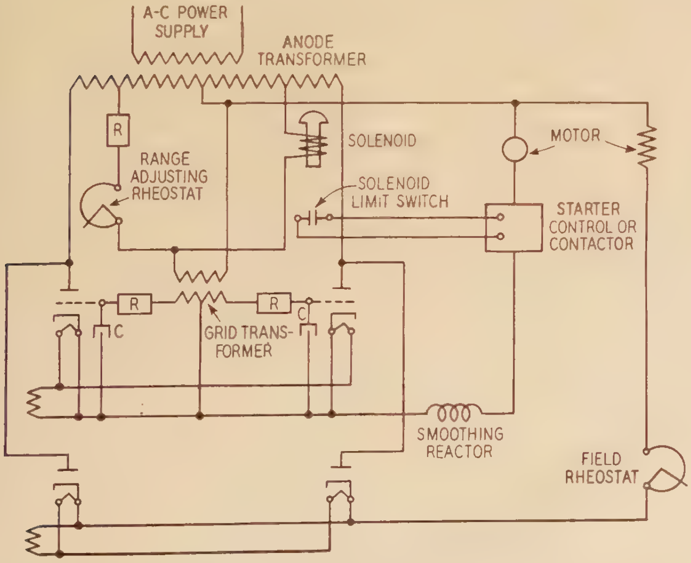


Figure 5. Thyratron armature-control circuit with solenoid control

If the reactance is varied from zero to infinity, the voltage from the midpoint of the bridge power supply to the junction of the resistor and the reactor will vary from the in-phase position to 180 degrees lagging with reference to the applied voltage. If the thyratrons supply a resistance load this range of control is required. In d-c motor applications there is always some reactance present which materially reduces this required phase angle shift. In addition, it is possible to still further reduce the required reactance change by partially tuning the reactor with capacitors.

While the data for this paper were taken on a one and one-half horsepower motor, these feed-back control circuits are not limited to motors of this size but can be applied to motors of any size, provided thyratrons of sufficient size are available. At the present time large thyratrons of 100 amperes rating require an appreciable amount of grid power. For this reason the elements in the control circuit must have an appreciably higher rating. The elements as described can be used to control the field excitation of motors up to approximately 100 horsepower and the armature power of motors up to three horsepower. Still larger motors can be controlled either by using small auxiliary thyratrons, or by controlling the field excitation of the generator in a Ward Leonard system.

Antihunting Circuit

In any feed-back system hunting may be caused by time delay in either the control or controlled circuit. It is more apt to occur as the difference in speed from no load to full load is decreased. A common method of eliminating hunting is to slow the response of the control circuit sufficiently to allow the circuit being controlled to respond to the new condition. Slow-speed feed-back systems are inherently stable, but in high-speed systems it may be necessary to either decrease the rate of response or to provide an antihunting circuit.

In electrical feed-back systems one method of eliminating hunting is to feed back into the control circuit a

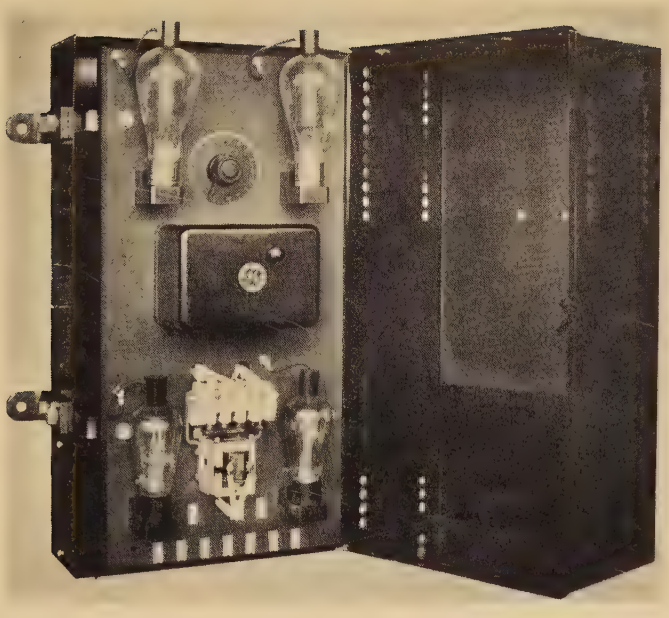


Figure 7. Thyratron control panel for one horsepower d-c motor showing two thyratrons for armature control and two phanotrons for field excitation

voltage which is proportional to the rate of change of one of the circuit voltages. This can be accomplished by impressing one of the circuit voltages on a resistor-capacitor circuit in which the voltage drop in the resistor varies as a function of the rate of change of the applied voltage. This particular method has been found satisfactory in electronic voltage regulators and to be equally as effective in the electrical feed-back systems described below.

Mechanical Feed-Back—Solenoid Control

The circuit of the simple mechanical feed-back system is shown in figure 1. In this circuit the excitation as furnished by the thyratrons is in the same direction as that obtained from the d-c power supply. Should a thyratron fail, the maximum speed of the motor is limited to that value as determined by the setting of the field rheostat and in normal application is approximately ten per cent above the normal maximum speed. The use of this separate source of excitation has still another advantage in that the discontinuity in the field current as mentioned previously is eliminated.

Referring to figure 2, curves A, B, and C show the variation in speed for different settings of the solenoid, and curves A^1, B^1, and C^1 show the variation in the thyratron output or field voltage. By partially tuning the solenoid coil with capacitors, as shown by the dotted lines in figure 1, it is possible to obtain the same degree of control with a smaller variation in the movement of the solenoid core. The untuned characteristics are shown in curves A and A^1 and the limiting tuned characteristics are shown in curves B and B^1. The dotted curve A^{11} shows the effect of the separate field excitation in removing the discontinuity in the field voltage curve. Curves C and C^1 show how these characteristics may be modified still further by changing the value of the fixed resistor in the phase shifting circuit. While these characteristic curves are not linear, their departure usually will not cause any difficulties. In the few cases where a linear relationship is required a correcting cam can be used.

As mentioned previously, the magnitude of the thyratron grid voltage must be large enough to compensate for variations in the critical grid voltage caused by usage and changes in temperature. It is possible to reduce the effect of these variations by replacing one of the thyratrons, figure 1, with a phanotron and to connect one side of the field circuit to the anode of the phanotron instead of to the midpoint of the anode transformer. In this way it is only necessary to control one tube. The secondary voltage of the anode transformer is the same in both cases. This circuit has the disadvantage that the secondary current flows only for one half the time and in only one direction. In addition the circuit is slower to respond for a decrease in excitation because of the short circuiting effect of the phanotron. The anode transformer can be eliminated if the power supply voltage has the correct value. The circuit characteristics are similar to those shown in figure 2.

In the control circuits just described the thyratrons were used to increase the field excitation. A failure of these tubes allows the motor to increase its speed to the value determined by the setting of the field rheostat. Even though the probabilities of a failure are rather remote, there are a few applications where it may be desirable to reduce the motor speed to its basic value if the thyratrons should fail to pass current. The elementary form of such a circuit is shown in figure 3. In this case the thyratrons control the field excitation indirectly

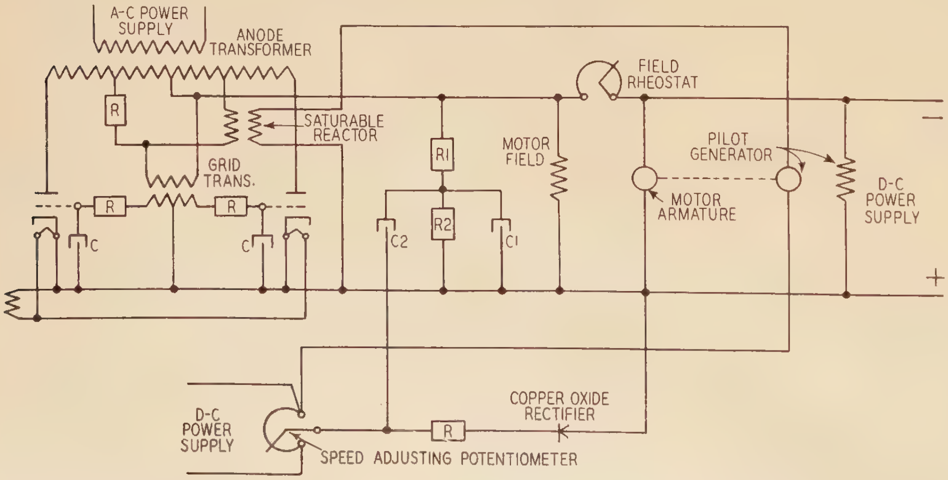


Figure 8. Thyratron field-control circuit, for holding constant speed

by varying the voltage drop in the field rheostat. With a failure of these tubes the motor speed will be reduced to its minimum value as determined by the setting of the field rheostat. The anode transformer must be designed correctly to limit the voltage applied to the field rheostat to such a value that the field current will not be reduced below its safe value, otherwise the motor will run away. The utility factor of this circuit is reduced because the change in motor field excitation is obtained indirectly. The maximum thyratron current will be approximately two times the rating of the motor field. The electrical characteristics of this circuit are shown by figure 4.

The elementary diagram of an armature control circuit in which the solenoid can also be used to vary the output voltage is shown in figure 5. The field excitation can be obtained either from a separate d-c source or from another pair of phanotrons which can use the same anode transformer for their source of voltage.

When armature control is used, some means must be provided to prevent impressing full voltage suddenly on the armature. In some applications this protection is taken care of by using a pair of contacts on the solenoid that are connected in the coil circuit of an anode contactor and are closed only when the solenoid air gap is reduced to zero, corresponding to zero armature voltage. By means of an electrical interlock on the anode contactor, the contactor is held in the closed position after the motor is started.

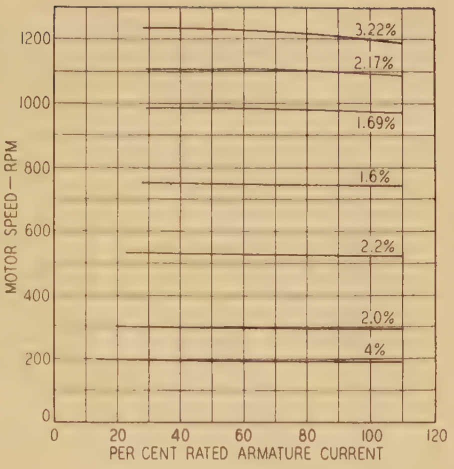


Figure 11. Characteristic curves of armature-control circuit, figure 10, showing speed regulation for different speed settings

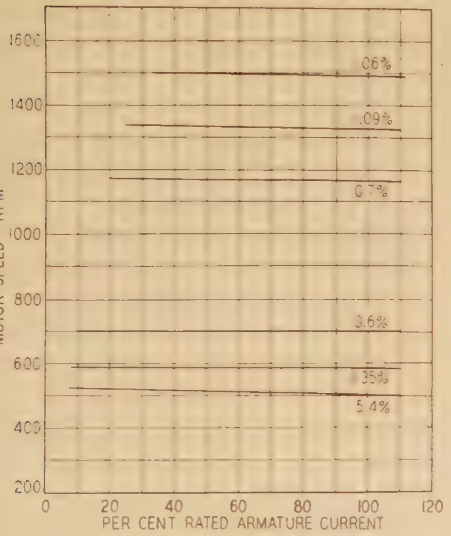


Figure 9. Characteristic curves of field-control circuit, figure 8, showing speed regulation for different speed settings

If this method of protection cannot be used a standard d-c motor starter can be substituted. In either case protection against overload and loss of field excitation can be applied in the normal manner.

The characteristics of this type of control are shown in figure 6. A typical panel with two thyratrons for armature control and with two phanotrons for field excitation are shown in figure 7. An adjustable resistor is used in the phase-shifting bridge circuit to vary the range of control that can be obtained with the phase-shifting solenoid. The adjusting knob for this rheostat, the cathode time-delay relay, and the anode contactor are also shown on the front of this panel. The anode transformer and smoothing reactor are usually wall mounted.

These mechanical feed-back circuits have proved to be very useful in wire drawing, the making of celluloid, rubber and rubber fabrics, and other similar processes. In these applications the problem is to hold the tension constant as the material passes from one part to another part of the same machine, or from one machine to another, even though the driving speed of one part of the machine may vary. For example, if the material is being wound on a reel, it is necessary to change the speed of the reel-drive motor as the diameter increases. In this case the phase-shifting solenoid is mechanically connected to a rider roll which rests on the material. If the tension is above normal, the rider will rise, thereby changing the solenoid air gap, which in turn either increases or decreases the thyratron output voltage, restoring the motor speed to the correct value. If the reel-drive motor

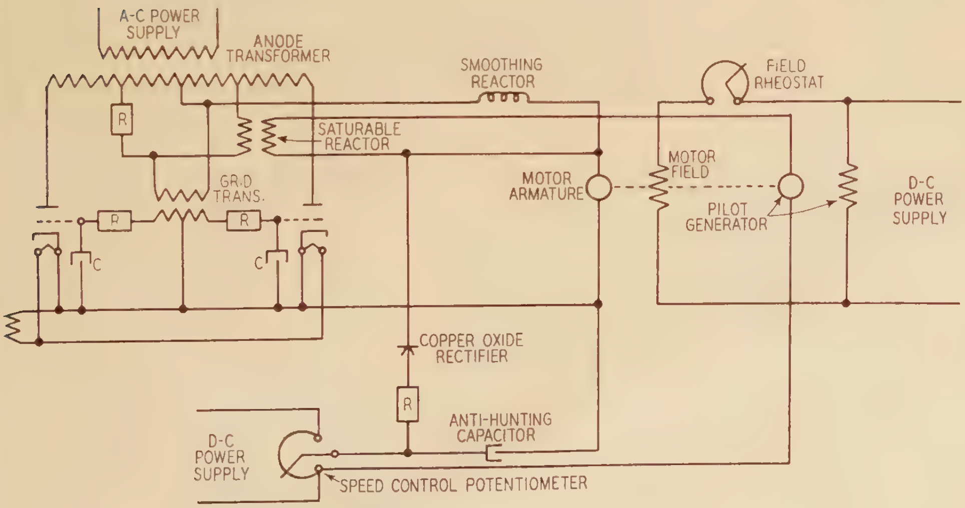


Figure 10. Thyratron armature-control circuit, for holding constant speed

tends to run too slow, the tension will be decreased and the rider roll will lower, producing the opposite effect. The important point is that this type of control not only is capable of maintaining constant tension but also provides a synchronous drive. In some applications constant tension is of minor importance and synchronism is of major importance.

Where constant tension is of importance the material being controlled must pass in a vertical plane either side of the rider roll so that the tension will always be equal to one half the unbalanced weight of the rider roll. In this case the only error is that due to friction and changes in the pull of the solenoid core. Normally the voltage applied to the solenoid coil is appreciably below its rated value for solenoid use and the change in pull from zero air gap to the maximum gap is less than two ounces and can usually be neglected.

Electrical Feedback—Saturable-Reactor Control

The previous discussion has covered the use of thyratrons for controlling either the field excitation or the armature power of d-c motors in which a mechanical feed-back control system has been used. There are many other applications where it is desirable to maintain constant speed, constant armature voltage, constant field voltage, to control a motor as some function of either a d-c or an a-c voltage, or to maintain approximate synchronism between two different systems by means of pilot generators. In the following circuits a small saturable reactor is used in place of the solenoid-type reactor. A suitable reactor is one that a change from zero to three milliamperes in the d-c winding will vary the reactance of the a-c winding from 1,000 to 10,000 ohms. If the a-c coils are connected in series this change in reactance can be obtained within a few cycles referred to a 60-cycle power supply. Since this reactor will have the same a-c impedance for a given saturating current of either polarity, it is necessary to limit current flow to one direction by connecting a unidirectional device such as a copper oxide rectifier or a rectifying tube in series with the d-c winding.

The elementary diagram of a field-control circuit for holding constant motor speed is given in figure 8. As shown the speed determining means is a pilot generator and the standard of reference is the voltage drop in a potentiometer. In normal operation the voltage of the pilot generator will be slightly greater than the voltage obtained from the potentiometer. If the load on the motor is increased the accompanying decrease in speed will be reflected by a decrease in the voltage of the pilot generator, which in turn will decrease the current through the d-c winding of the saturable reactor. This reduction in the saturating current will reduce the thyratron output or field voltage, thereby restoring the speed to approximately its previous value. If the load on the motor is decreased, the accompanying rise in speed will have the opposite effect. The speed never will be restored to exactly its previous value, when a change in load occurs, because there always must be a change in the relative voltages of the potentiometer and the pilot generator in order to produce the necessary change in the saturating current. With the correct saturable-reactor design a small voltage, when impressed on the d-c winding, is sufficient to vary the thyratron output voltage from zero to a maximum. By adjusting the arm of the potentiometer the speed of the motor can be held constant within a few per cent from no load to full load over its entire speed range as shown in figure 9. It will be noted that the change in speed from no load to full load for the lowest speed curve was between five and six per cent. This abnormal change was due to the fact that the thyratron output voltage was near its maximum value. The d-c voltage for the speed adjusting potentiometer can be obtained either from a suitable d-c voltage source or from the voltage of another pilot generator which is connected to another system. In this way the relative speed of two independent systems can be held approximately constant.

Hunting is prevented by means of capacitor $C2$ and resistor $R3$. Resistors $R1$ and $R2$ together with capacitor $C1$ have been added to reduce the effect of the field ripple voltage.

In certain processes such as the making of incandescent lamp bulbs an adjustable wide range of speed control is required in which the speed variation from no load to full load is a minimum. The elementary diagram of the armature control, figure 10, fulfills these requirements. Again the control elements are the same, including the use of the antihunting capacitor. The characteristics of this circuit are shown in figure 11.

These two circuits, figures 8 and 10, have been used for controlling the speed of high-frequency generators and conveyor systems and could probably be used in a great many similar applications. Up to the present time insufficient data on the characteristics of these circuits has materially limited their application.

In certain applications such as the control of small wood-turning lathes, an adjustable speed-control system is very desirable. The circuit shown

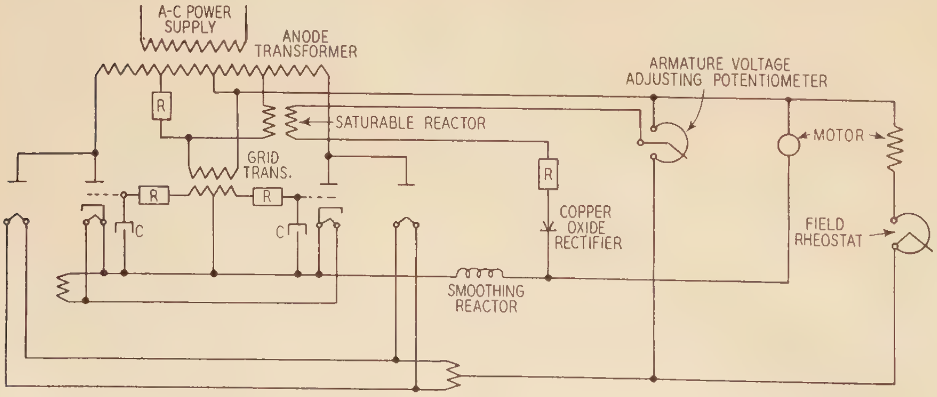


Figure 12. Thyratron armature-control circuit, for holding constant armature voltage

in figure 12 provides an adjustable source of power for the armature, and excitation for the field. The control circuit is the same as that shown in figure 10 except that the voltage applied to the speed-control potentiometer is obtained from the field circuit. Due to regulation in the anode transformer the change in speed from no load to full load is greater than that shown in figure 11. If better regulation is required, power for the potentiometer can be obtained from a separate direct current source or from a small rectifier. The effect of this regulation is shown in figure 13.

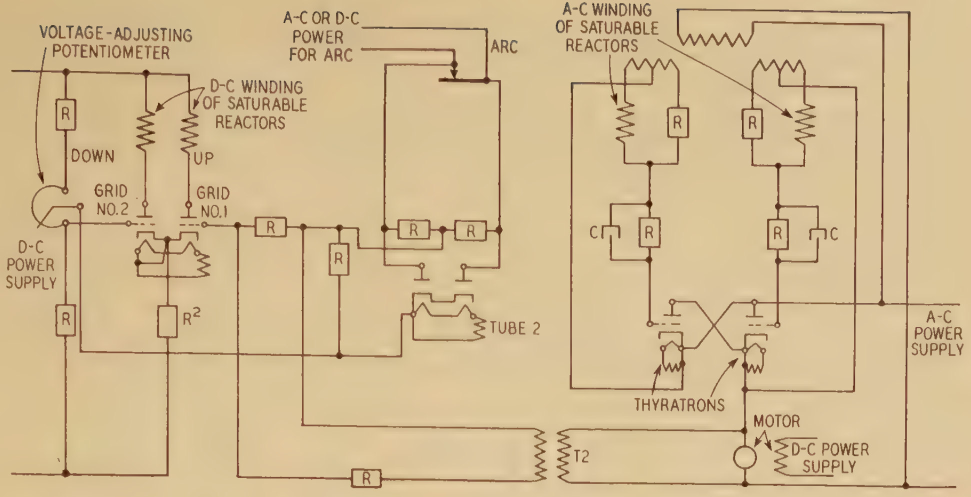


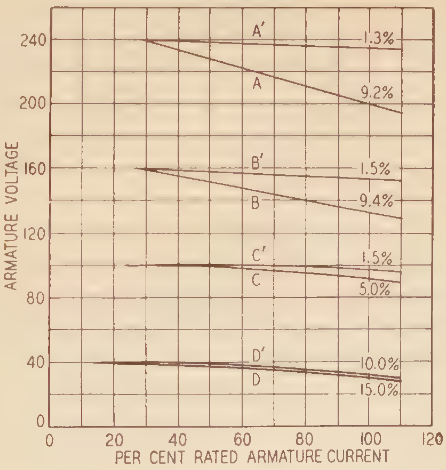
Figure 14. Thyratron control for reversing d-c motor—atomic or metallic arc-welding control

In all of the motor-control circuits which have been discussed the problem was primarily that of either maintaining a definite speed relationship between two systems or of maintaining constant motor speed. The third general classification is the control of a d-c motor as a function of either an a-c voltage or a d-c voltage which is dependent upon the speed or position of the motor. The control of either an arc furnace or an automatic arc-welding head fall in this class. The problem in either case is to maintain constant either the arc voltage or the arc current. The present mechanical method of arc-furnace control is to use either a contact making ammeter or contact making voltmeter together with reversing contactors. These contactors are required to operate a large number of times, consequently the wear is great. Somewhat the same situation applies for automatic arc welding heads but in addition either alternating current or direct current may be used. The circuit shown in figure 14 has been developed for either atomic or metallic arc welding. In this application a small d-c motor is used to feed the electrode wire to the arc. Since this motor is small only two thyratrons are required to run the motor in either direction while two pairs of thyratrons are required to control each motor of an arc furnace.

Referring to figure 14, two small saturable reactors are used to control the two thyratrons. With equal saturation in the two reactors each thyratron will pass the same amount of current, but of opposite polarity. In this case the average value of the torque in the motor will be zero. If the saturation of one reactor is greater than that of the other the motor will run in one direction at a speed determined by the difference in saturation. Conversely, if the saturation is in the reverse order, the motor will run in the opposite direction. The saturation current is controlled by means of a duotriode which has two anodes, two grids, and a common cathode.

In normal operation the arc voltage, either alternating or direct current, is rectified by means of tube 2 and impressed on grid number 1 of the duotriode. If the arc voltage is above normal, as determined by the setting of the voltage adjusting potentiometer, the saturating current through the "up" reactor will decrease, thereby reducing the current through the "up" thyratron with the result the motor armature will run in the down direction. The accompanying reduction in current through resistor *R*2 increases the bias on the grid number 2 in a positive direction tending to still further saturate the "down" reactor. If the arc voltage is low the "up" reactor will become saturated and the motor armature will run in the reverse direction. Due to the unbalancing effect of resistor *R*2 a variation of several per cent in the arc voltage is sufficient to cause the motor armature to run at full speed in either direction. In atomic welding the electrodes burn away so slowly that the motor armature normally stands still. In metallic arc welding the welding electrode burns away much faster and in normal operation the armature gradually turns in the downward direction, but can if necessary run from zero to full speed in either direction. While hunting is normally not present overcontrol is materially reduced by means of transformer *T*2, which introduces a retarding voltage into the grid circuit when a change occurs in the motor speed. The circuit will respond to a change in arc voltage within a few cycles referred to a 60-cycle power supply. Experience

Figure 13. Characteristic curves of the armature-control circuit, figure 12. Curves A, B, C, and D show voltage regulation when field voltage was used for control. A′, B′, C′, and D′ show voltage regulation when separate d-c voltage was used for control



from a limited number of applications indicates that this type of control offers many advantages in comparison to some of the existing mechanical methods. This circuit responds within a few cycles, referred to a 60-cycle power supply, to a change in arc voltage, and can be used for either atomic or metallic arc welding when either direct or alternating current is used.

Conclusion

There are a large number of applications in the industrial field that require smooth control of d-c motors. New circuits are now available which utilize the thyratron with its inherent advantages which are high efficiency, full control with the minimum of control energy and quickness of response. The elements of these circuits are simple, easy to service, and of conventional design and consequently the circuits are easy to apply. It is possible by means of these circuits to maintain constant speed and constant relative speed between two systems. It is also possible to hold the voltage or current constant in an arc furnace or in an automatic arc welding head.

The use of these circuits in no way limits or alters the use of conventional d-c motor starting on protective systems. These circuits should not only be competitive, but should accomplish results that are difficult if not impossible to obtain with existing mechanical methods.

In the past, cost of the control and lack of confidence have been limiting factors in the application of thyratrons to the control of d-c motors. With increased use and refinements in design the cost will be reduced. Experience has already indicated that confidence in this type of control is increasing as thyratron control is being used with complete success at the present time in certain processes in which a failure of either the control or the thyratrons would cause a shut down of the entire system.

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Discussion

A. J. Williams, Jr. (Leeds and Northrup Company, Philadelphia, Pa.): I was much interested in Mr. Garman's paper, particularly in certain passages referring to antihunting devices which, however, I do not believe he mentioned in his oral presentation.

Several years ago my company had the problem of using a constant frequency source of low power level to control a d-c to a-c converter. One possibility was the use of a thyratron inverter, but for the type of application involved a motor generator seemed better suited since the tube capacity was less, since the output voltage could be made independent of d-c line voltage, and since a tube failure would cause only a loss of constant frequency and not a complete loss of voltage.

We used a shunt motor with thyratron control on the field. The thyratron was supplied with alternating current on the plate from the self-excited alternator and alternating current on the grid from the constant-frequency source. In operation, if the machine slowed down, the plate voltage increased its lag with respect to the grid voltage, more current was passed which weakened the motor field so restoring the phase in part and the speed completely.

We found that full-load variation could be taken care of readily but that the permissible variation in the d-c line voltage was not very great due to the inherent characteristics of a shunt motor with more or less saturation in the field. Anything which increased the range of line voltage stiffened the phase control and increased the tendency to hunt. There was a definite limit which could not be exceeded.

Our next step was to build in an antihunting system. I will not describe this. However, what I do want to mention is the very gratifying results which were obtained from the use of the system. The permissible variation in d-c line voltage was increased by a factor of four.

In closing, therefore, I want to repeat that I was much interested with the short passages in Mr. Garman's paper which referred to antihunting devices and from my own experience, I highly recommend their use for difficult control problems.

G. W. Garman: The prevention of hunting or its elimination as discussed by Mr. Williams, in any closely regulated system, can be a major problem in itself. It can be dealt with only in generalities, except in special cases where all of the constants of the system are known. In a large number of industrial applications, it is sufficient to hold the speed of the controlled motor within one of two per cent, as the load of the motor is varied from its no-load to its full-load value. In these applications hunting can be prevented by the methods illustrated in the paper. In those applications where the speed must be held constant within less than one-half of one per cent, the problem of hunting or of speed variation may become more serious, as other factors, which normally have little effect, now become of importance.

For example: Normally we think of the voltage of a d-c pilot generator as being continuous, except for the small ripple voltage produced by the commutator segments, the effect of which can be eliminated by means of a filter circuit as the equivalent frequency is high. However, the ripple voltage caused by an eccentric armature, even though it is very small, may be sufficient to produce an objectionable variation in the speed of the controlled motor. In addition, it may be difficult to determine whether motor speed variations of this type are caused by an unstable control circuit or by some other factor such as variations in the pilot generator voltage.

It is largely through experience that we learn to appreciate the effect of some of these factors, which normally are negligible, and therefore are able to solve satisfactorily these more difficult problems.

Electronic Speed Control of Motors

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IN THE EARLY years of the electrical industry there was no acceptable a-c motor. After the development of the induction motor and the synchronous motor two machines were available which are unsurpassed in simplicity, reliability, and economy. These motors are, however, both inherently constant speed machines. In later years, a variety of a-c motors have been developed and a number of these have had adjustable or variable speed characteristics. There is, however, as yet, no adjustable-speed a-c motor so flexible as the Ward-Leonard combination, and there is still room for much improvement in adjustable speed a-c motors.

The development of power tubes provides a new approach to the problem of variable-speed motors. This appears to be one of the most promising fields for large tubes and rapid progress may be expected in this direction. It is the purpose of this paper to outline briefly some of the more promising methods of using tubes to control the speed of a motor. A great variety of combinations may be produced, and there will be no attempt to give a complete discussion of this field. The arrangements described, are some of the simplest combinations and provide attractive characteristics.

Thyratron Motor

Those familiar with the art will recognize that a start has already been made in using power tubes to control the speed of an a-c motor. The first tube motor to be developed in America was constructed as a synchronous motor and employed a group of 18 thyratrons as a commutator.[1–3] The Appalachian Electric Power Company has been operating a 400 horsepower motor of this type for over one year. The characteristics and operation of this motor are fully discussed in other articles.[2–4] It is therefore not necessary to dwell further on this method of using thyratrons to produce an adjustable-speed motor.

Rectifier Speed Control for Wound-Rotor Induction Motor

The wound-rotor induction motor with secondary resistance has been used as an adjustable-speed drive in many applications. There are, however, two well-known disadvantages to this use of the induction motor: first, the efficiency of the motor is reduced in proportion to the speed reduction; second, the motor has poor speed regulation with load at reduced speeds. It is possible to improve the operation of this motor at reduced speeds by substituting a rectifier and d-c motor for the secondary resistance. This combination of induction motor, rectifier and d-c motor is quite similar to a Kraemer drive. The d-c motor may be used to help drive the mechanical load, or to drive an auxiliary a-c generator which returns, to the supply system, the power recovered from the induction-motor secondary.

Speed adjustment of the induction motor is obtained through the field of the d-c machine. The action is as follows: assume that the d-c motor in figure 1 is operating at constant speed and with a given field excitation. It has then a definite counter electromotive force and the rectified d-c voltage must match this before current can flow. The d-c voltage of the rectifier bears a definite ratio to the alternating voltage applied to the rectifier which, in turn, is determined by the slip of the induction motor. If, therefore, the a-c motor be operating at synchronous speed it must slow down until the secondary induced voltage is sufficient, when rectified, to match the voltage of the d-c machine. Any further reduction in the speed of the induction motor will cause a current to flow in its secondary and produce a corresponding induction-motor torque. In this manner the induction motor operates at an approximately constant speed or slip determined by the counter electromotive force of the d-c motor.

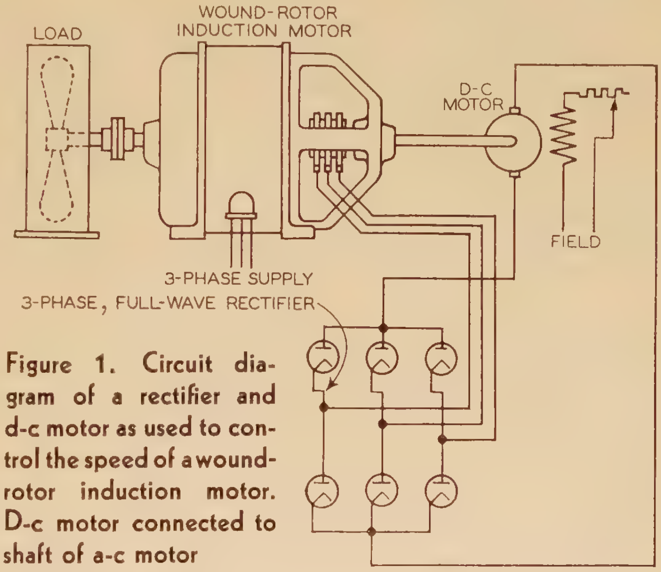

Figure 1. Circuit diagram of a rectifier and d-c motor as used to control the speed of a wound-rotor induction motor. D-c motor connected to shaft of a-c motor

It is evident from the unidirectional character of a rectifier that a small increase in the speed of the a-c

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[1] For all numbered references, see list at end of paper.

motor does not result in a reversed torque. Dynamic braking will, however, occur if the speed of the induction motor exceeds the synchronous speed by a slip equal to the slip required for motor action.

Apparatus Economy

The principal advantage of the rectifier control arises from the fact that the operation and rating of the rectifier are quite independent of the frequency. The rating of the rectifier must approximately equal that of the induction motor. The size of the d-c machine however will be determined by the speed variation required. In case the d-c motor is connected to the same shaft as the a-c motor the approximate rating of the d-c motor may be obtained from the relation,

$$M = \alpha - 1 \tag{1}$$

where α represents the ratio of the maximum to the minimum speed required and M, the ratio of the rating of the d-c and a-c motors. For a two-to-one speed ratio the d-c motor must equal the a-c motor in capacity.

When the d-c motor is connected to the shaft of the a-c machine, we avoid the necessity of an auxiliary a-c generator. The d-c motor is, however, used less effectively at the lower speeds. If the speed range is greater than two to one it will be more economical to absorb the output of the rectifier in a constant speed d-c motor, connected to an a-c generator, to form an auxiliary motor-generator set. A motor-generator set may be preferred if the main motor operates at a low speed or when its location is such that it is inconvenient to connect the auxiliary d-c motor to its shaft.

When an auxiliary motor-generator set is used M, the ratio of the rating of the d-c motor to the rating of the main motor is

$$M = \frac{\alpha - 1}{\alpha} \tag{2}$$

where α as above is the ratio of the maximum to minimum speed. For a two to one speed control the d-c motor must be half the rating of the main a-c motor. The a-c generator in the auxiliary motor-generator set must be large enough to return the power recovered to the supply system. In case of a constant-torque load the a-c generator must have approximately the same rating as its d-c motor. If, however, the load torque decreases with speed as in a fan drive the a-c generator may be considerably smaller than the d-c motor. At high speeds the d-c machine delivers very little power because it has a weak field. At low speeds the d-c motor furnishes little power because it has a small current.

Wye-Delta Secondary Connection

When the load and therefore the current decreases as the speed is reduced it is possible to extend the range of speed control by changing the induction-motor secondary from a wye to a delta connection at some reduced speed. In this way a greater speed range may be obtained from a given d-c motor.

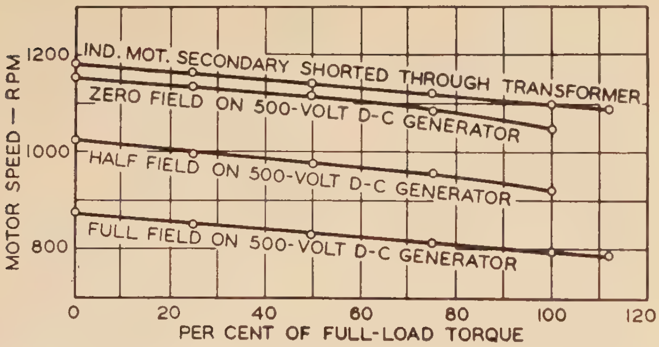


Figure 2. Speed-torque characteristics of a wound-rotor induction motor with rectifier speed control

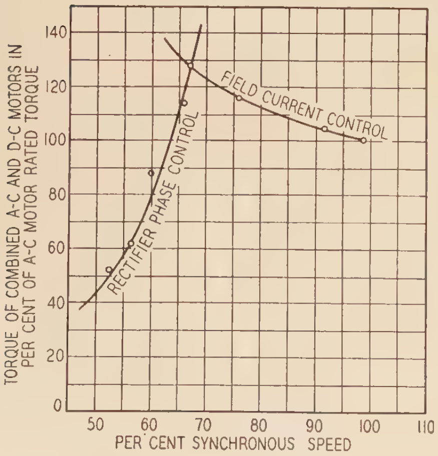


Figure 3. Torque available at rated current when induction - motor speed is reduced by rectifier and d-c motor connected to shaft of a - c motor. Speed control partly by d-c motor field and partly by rectifier phase control

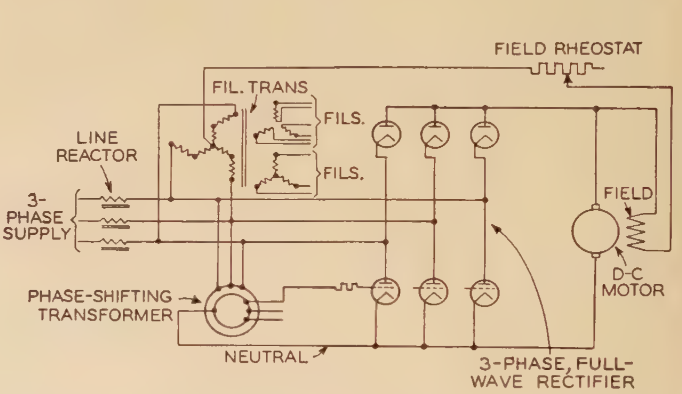


Figure 4. Circuit diagram of a d-c motor operating from a phase-controlled rectifier. Three-phase full-wave rectifier with half-wave phase control shown

Circuit Diagrams and Characteristics

There is given in figure 1 a circuit diagram for a three-phase full-wave rectifier as used to control the speed of a wound-rotor induction motor. The d-c motor is here shown connected to the shaft of the a-c motor. The same rectifier circuit may be used with an auxiliary motor-generator set. The curves on figure 2 show the speed-torque characteristics of the motor shown in figure 1. The speed-torque curves with an auxiliary motor-generator set are similar.

In taking data for the curves shown, a 25-horsepower

Figure 5. Curves showing the operation of a three-phase full-wave rectifier with full-wave phase control

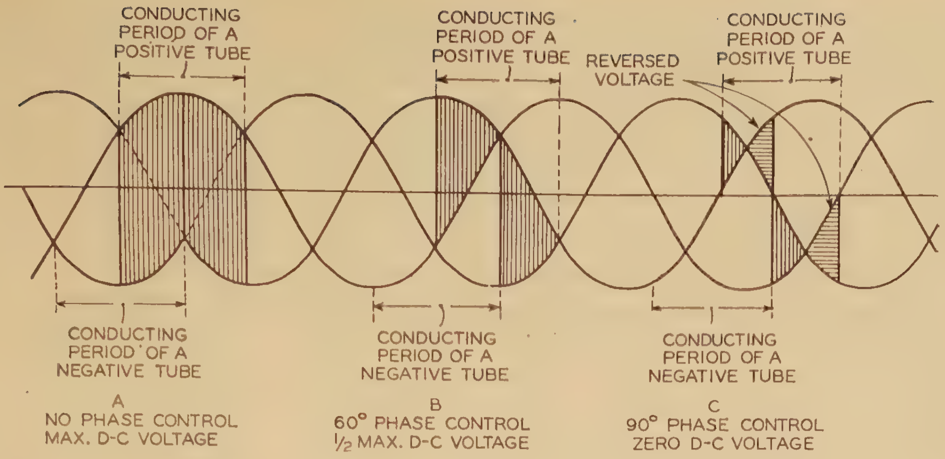
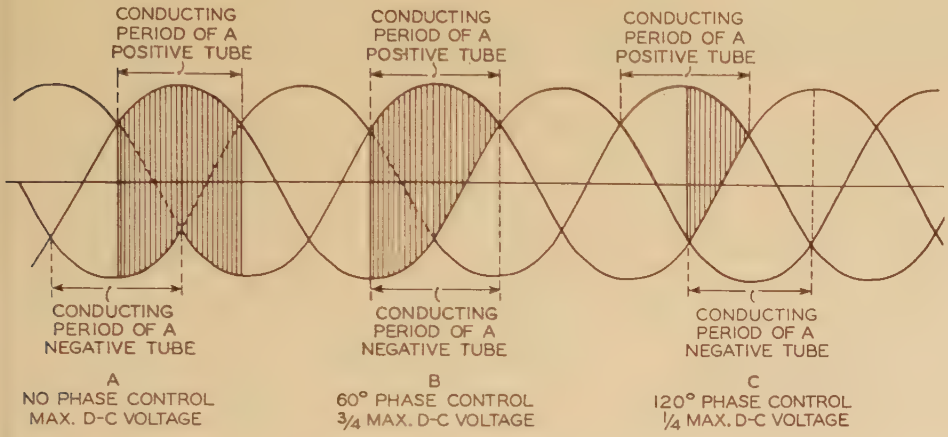

CONDUCTING PERIOD OF A POSITIVE TUBE
CONDUCTING PERIOD OF A POSITIVE TUBE
REVERSED VOLTAGE
CONDUCTING PERIOD OF A POSITIVE TUBE
CONDUCTING PERIOD OF A NEGATIVE TUBE
CONDUCTING PERIOD OF A NEGATIVE TUBE
CONDUCTING PERIOD OF A NEGATIVE TUBE
A
NO PHASE CONTROL
MAX. D-C VOLTAGE
B
60° PHASE CONTROL
1/2 MAX. D-C VOLTAGE
C
90° PHASE CONTROL
ZERO D-C VOLTAGE

Figure 6. Curves showing the operation of a three-phase full-wave rectifier with half-wave phase control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CONDUCTING PERIOD OF A NEGATIVE TUBE
CONDUCTING PERIOD OF A NEGATIVE TUBE
A
NO PHASE CONTROL
MAX. D-C VOLTAGE
B
60° PHASE CONTROL
3/4 MAX. D-C VOLTAGE
C
120° PHASE CONTROL
1/4 MAX. D-C VOLTAGE

motor with a 110-volt three-phase secondary winding was used. The secondary voltage of this motor was too low to rectify efficiently. This difficulty may be encountered in some motor designs, but it seems possible to obtain motors of 50 horsepower or greater with a secondary voltage high enough to rectify economically.

In the case of the 25-horsepower motor the secondary voltage was stepped up to 1,100 volts by means of autotransformers. This device would be expensive and cannot be considered typical. The use of the transformers in the tests increased the full load slip somewhat but otherwise did not materially affect the operation.

PHASE CONTROL OF RECTIFIER

It is evident that, by phase controlling the rectifier, it is possible to extend the range of speed control. The curves in figure 3 show the variation of torque with speed for an induction-motor control with constant effective current in the primary of the induction motor. In obtaining data for these curves the d-c motor was connected to the shaft of the induction motor. This accounts for the increasing torque available as long as the speed is reduced by motor field control. It is evident from the curve shown in figure 3 that the motor torque, available at rated current, decreases rapidly if the speed is reduced by phase control of the rectifier. When an auxiliary motor-generator set is used, phase control of the rectifier causes the main motor to operate even less effectively than as shown in figure 3.

STARTING

When starting an induction motor which operates with a secondary rectifier for speed control, the starting current may be limited by series resistance in the a-c lines. A somewhat simpler arrangement would employ a resistance in the d-c lines. If there is an auxiliary motor-generator set which can be started before the main motor, no other starting device is necessary. The counter electromotive force of the d-c machine, acting with the inherent impedance of the induction motor will limit the starting current to a moderate value.

Phase-Controlled Rectifier and D-C Motor

The d-c motor has long been the standard of excellence as an adjustable-speed drive, but its use is limited because of the prevalence of a-c power. When a motor-generator set is used for converting from a-c to d-c power the Ward Leonard combination gives a flexibility and range of speed control difficult to equal. The cost or low apparatus economy of the Ward Leonard combination is its greatest limitation.

There is little or no novelty in supplying a d-c motor from a rectifier and varying the speed by field control. When, however, the motor and rectifier are considered as a unit, a new degree of freedom may be introduced in varying the armature voltage by phase control of the rectifier. This combination permits a greater range of speed adjustment than can be economically obtained by field control alone. In the upper part of the speed range where the power required is a considerable portion of the motor rating, field control is desirable because this will give the highest efficiency and power-factor. For the lower speed ranges, phase control of the rectifier, to give a reduced armature voltage is desirable. The low efficiency and power-factor produced by phase controlling the rectifier are of little consequence at the low speeds

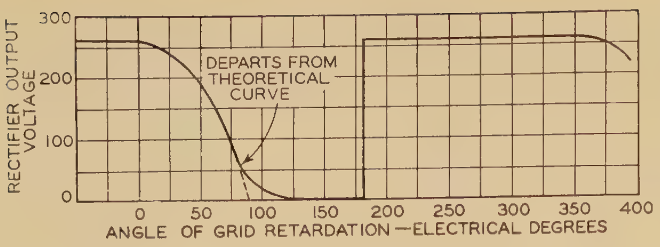


Figure 7. Curves showing the variation of rectifier voltage with grid phase angle for a three-phase full-wave rectifier with full-wave phase control

because of the reduced power. By combining field control of the motor and grid-phase-control of the rectifier it is possible to obtain a 100 per cent speed range (zero to rated speed) with a motor of moderate size, and without unduly increasing the losses and reactive power of the rectifier.

Three-Phase Full-Wave Rectifier Circuit

Any convenient rectifier circuit may be employed. Where three-phase power is available the three-phase full-wave rectifier circuit gives the best apparatus economy. If the three-phase power is available at a voltage between 220 and 600 volts, this rectifier circuit may be operated from the a-c lines without rectifier transformers and the d-c voltage produced will be between 250 and 800 volts. The full-wave rectifier is penalized at low voltage by having two tubes in series and therefore a high arc drop loss. This objection is, however, more than compensated for, by the elimination of rectifier transformers, even though the operating voltage is as low as 220 volts.

The rectifier should be connected to the a-c power supply through line reactors as shown in figure 4. These reactors are very useful in suppressing current and voltage harmonics, and also serve to limit the fault current in case of an arc back or other failure. The three-phase full-wave circuit is attractive in view of the fact that line reactance is twice as effective in limiting the short-circuit current of the a-c system, as in producing regulation of the d-c voltage. A ten per cent reactance in the a-c lines produces only five per cent regulation of the d-c voltage, but limits the current to ten times normal in the case of a three-phase short-circuit.

HALF-WAVE PHASE CONTROL

In the circuit diagram shown in figure 4, phase control is applied to only half of the rectifier tubes. This arrangement is quite desirable. For lack of a better description this operation may be called half-wave phase control of a full-wave rectifier. This method of phase control is superior to the full-wave phase control where all tubes are controlled, in that it produces lower reactive kilovolt-amperes and smaller harmonic currents in the a-c supply system. The advantages of half-wave phase control are greatest at low d-c voltage.

The operation of a rectifier with half-wave phase control is best explained by comparison with full-wave phase control which is somewhat simpler. The curves given in figures 5 and 6 show the operation of a three-phase full-wave rectifier with full-wave and half-wave phase control, respectively. It is important to note that with full-wave phase control, and more than 60 degrees phase shift the voltage applied to the d-c circuit reverses during part of the time as shown in figure 5*C*. This causes low power-factor current in the a-c circuit.

When half-wave phase control is employed the voltage applied to the d-c circuit may go to zero but it never reverses. If the conducting period of the tubes is delayed more than 60 degrees there comes a time when the positive and negative tubes of the same phase are conducting simultaneously as shown in figure 6*C*. During this interval the a-c circuit is effectively disconnected, and the d-c circuit is operating from the energy stored in the d-c reactor. If the a-c circuit were connected during this time its voltage would be of the wrong polarity. It is therefore better that the a-c circuit be effectively disconnected.

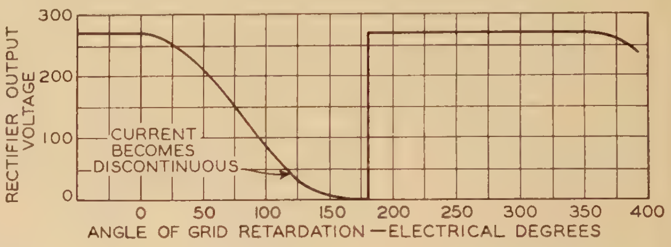


Figure 8. Curve showing the variation of rectifier voltage with grid phase angle for a three-phase full-wave rectifier with half-wave phase control

When a three-phase full-wave rectifier with full-wave phase control is employed E_{dc} the d-c voltage is given approximately by the relation

$$E_{dc} = 1.35\, E_L \left(\cos\theta - \frac{XI}{2I_0}\right) - 2e_t \qquad (3)$$

where E_L is the effective a-c line voltage, θ is the angle by which conduction of the tubes is delayed by grid control, e_t is the arc drop of one tube, I_0 is the rated current, I is the actual current in the d-c circuit, and X is the per-unit reactance in the a-c lines. It is evident from this relation and from the curves of figure 5 that the d-c voltage is zero when the phase shift θ is 90 degrees. The relation (3) assumes that the current in the d-c circuit is continuous but it is evident that as the d-c voltage is decreased the ripple voltage increases. The current in the d-c circuit will, therefore, become discontinuous at some reduced voltage, depending on the size of the d-c reactor and the load current. The average voltage in the d-c circuit will then depart from the curve determined by relation (3), because this relation assumes a continuous current and does not hold when the current is intermittent.

Figure 7 shows a typical phase-control curve for a three-phase full-wave rectifier operating with full-wave phase control. The data for the curve was taken with a resistance load in the d-c circuit. If there had been a counter electromotive force load the current would have become intermittent at a higher voltage.

When the voltage applied to the grid circuit of the tubes is sinusoidal a phase shift of more than 180 degrees causes the tubes to be started at the normal time by the lagging tip of the grid-voltage wave. A phase shift of more than 180 degrees therefore, restores full d-c voltage, as shown in figure 7.

When a three-phase full-wave rectifier is operated with half-wave phase control, E_{dc} the d-c voltage is given approximately by the relation.

$$E_{dc} = 1.35\,E_L\,\frac{\left((\cos\theta+1) - X\frac{I}{I_0}\right)}{2} - 2e \tag{4}$$

where, as above E_L is the effective a-c line voltage, θ is the angle by which the conduction of the tubes is delayed by grid control, e_t, is the arc drop of one tube, I_0 is the rated current, I is the actual current in the d-c circuit, and X is the per unit reactance in the a-c lines. In case half-wave phase control is employed the grids must be shifted 180 degrees to reduce the d-c voltage to zero, as may be seen from relation (4) and the curves of figure 6.

The curve of figure 8 shows the variation of d-c voltage with grid angle when half-wave phase control is employed. The data for figure 8 was taken with the same load and rectifier circuit as for figure 7, except that half-wave phase control was used when taking data for figure 8.

It is evident from the curve in figure 8 that with a sinusoidal grid voltage full d-c voltage is restored by a grid shift just a little greater than that necessary for zero d-c voltage. This becomes a hazard when operating at a very low d-c voltage, unless some type of self-biasing grid circuit be used so that the positive voltage wave on the grid is shorter than the negative voltage wave. Even with a self-biasing grid circuit too great a phase shift will cause the d-c voltage to increase abruptly to its maximum value.

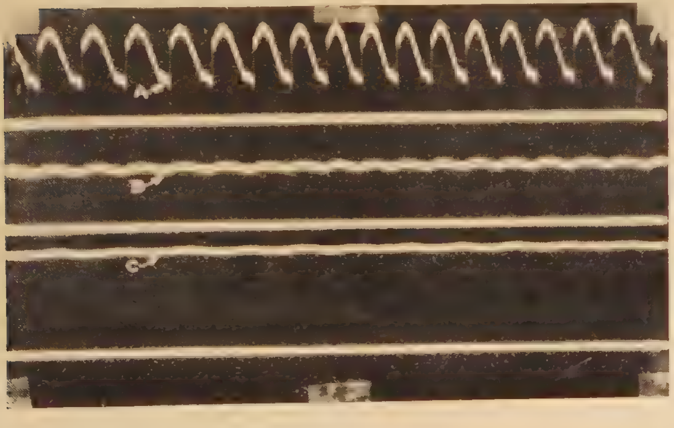


Figure 9. Oscillogram showing voltage impressed on motor field, trace A, field current, trace B, and voltage induced in armature at rated speed, trace C, when the field of a d-c motor is supplied from a three-phase half-wave rectifier

A possible objection to the use of a rectifier with half-wave phase control arises from the fact that the positive and negative current waves are not symmetrically spaced. Either the positive or negative current wave is displaced because of phase control. This leads to even harmonics in the supply current. These even harmonics do not, however, increase the effective value of the harmonic current but the even harmonics replace odd harmonics which would be present if the rectifier were operated symmetrically. The resulting harmonic current in the supply circuit is never greater with half-wave phase control than it would be if full-wave phase control were employed. At low d-c voltages the resulting harmonic current is lower with half-wave phase control than with full-wave phase control. With this picture of the operation of half-wave phase control we may return to a consideration of a d-c motor operating from a phase-controlled rectifier.

Ripple Current in Armature Circuit

If the conducting period of a rectifier is delayed by grid control, the average voltage in the d-c circuit is reduced but the deviation of the instantaneous voltage from the average or d-c voltage is greatly increased. This deviation of the instantaneous from the average voltage is usually referred to as the ripple voltage. The increase of ripple voltage with phase control is obvious in figures 5 and 6. The ripple voltage produced by the rectifier causes a current ripple in the d-c load circuit. An inductive reactance is frequently used to reduce the magnitude of this ripple current.

When the phase-controlled rectifier is supplying a d-c motor, commutation will limit the magnitude of the ripple current permissible. The inductance required for the d-c circuit may be determined from the relation

$$L = \frac{E_r}{\frac{dI_{am}}{dt}} \tag{5}$$

where

E_r = the maximum ripple voltage produced by the rectifier; $\frac{dI_{am}}{dt}$ is the maximum rate of change of armature current consistent with good commutation.

The maximum permissible rate of change of armature current can be determined from the motor design.

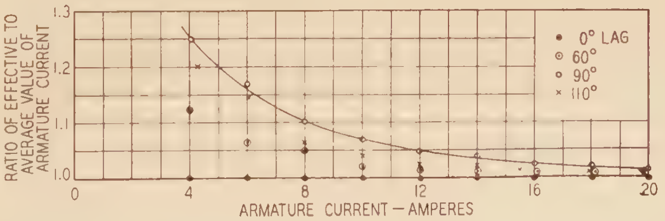


Figure 10. Curve showing ratio of effective to average value of armature current when a d-c motor is supplied from a three-phase full-wave rectifier with half-wave phase control

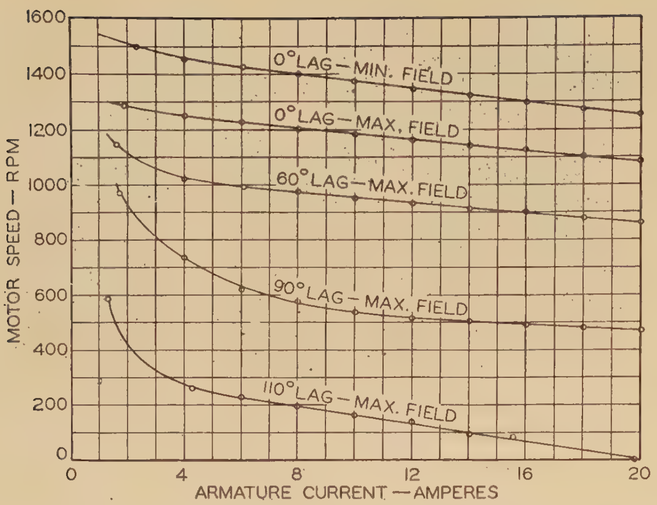


Figure 11. Speed–armature-current characteristics for a d-c motor operating from a three-phase full-wave rectifier with half-wave phase control

Field Excitation for D-C Motor

When operating a d-c shunt motor from a phase-controlled rectifier it is important that the field of the motor be supplied from a reliable source at a constant voltage. It is possible to supply the field from an auxiliary rectifier with a suitable interlock for removing the armature voltage if the field power fails. A more convenient source of field excitation is, however, available when half-wave phase control is used. It is then possible to connect the field between the a-c neutral and the d-c line common to the three tubes not phase controlled. This connection is shown in figure 4.

If the a-c system has no neutral, an artificial neutral can be created by the filament transformers, phase-shifting transformer, or other auxiliary equipment. It is desirable to have the transformers forming the artificial neutral, connected zigzag to avoid saturation.

When the shunt field is supplied by connecting it from the a-c neutral to one d-c line, the voltage impressed on the field will have a triple-frequency ripple of considerable magnitude. This ripple voltage will, however, cause only a small variation in the field current because of the high inductance of the field circuit. Eddy currents set up in the poles and frame of the d-c machine will further neutralize the small ripple present in the field current and maintain the flux through the field sensibly constant. The oscillogram in figure 9 shows the voltage impressed on the field circuit, the field current, and, the generated electromotive force obtained by driving the machine at rated speed. The small ripple shown on the generated electromotive force is not concurrent with the ripple current in the field circuit. The generated electromotive force shows no evidence of flux variation due to the ripple current. A direct measurement of the transformer electromotive force caused by the variation of the flux indicates a voltage of the order of 20 to 50 millivolts in the coil under commutation. An effect of this magnitude will have a negligible influence on commutation.

In case a series field winding is employed, the ripple current in this winding will also tend to produce variations of the flux. Measurements made with a ten per cent series field indicate a transformer electromotive force in the coil under commutation no greater than that caused by the ripple in the shunt-field current; i.e., 20 to 50 millivolts. With a larger percentage of series excitation the ripple current in the series field will be correspondingly reduced by the inductance of the series field. It appears, therefore, that no appreciable commutating trouble may be expected from field-flux variation with either shunt or series field excitation.

Operating Characteristics

The operating characteristics of a d-c motor are quite familiar. When, however, the d-c motor is supplied from a phase-controlled rectifier there are certain modifications introduced by the rectifier. It, therefore, seems desirable to give some operating data. The curves shown in figures 10 to 13, inclusive were taken on a 10-horsepower 550-volt 1,300-rpm d-c shunt motor operating from a three-phase full-wave rectifier with half-wave phase control. The circuit diagram is as shown in figure 4. The rectifier was supplied from a 440-volt, 3-phase, 60-cycle source of power. A picture of the rectifier and its associated equipment is shown in figure 14.

The curves shown in figure 10 give the ratio of the effective to average value of the armature current. The ripple current in the armature contributes nothing to the power of the d-c motor but increases the copper loss of the armature circuit. The armature copper loss of the d-c motor will be increased approximately as the square of the ratio of effective to average current shown in figure 10.

The ripple voltage increases rapidly as the d-c voltage is reduced by grid control, but does not vary appreciably with the load. It is evident, therefore, that with a given angle of phase control the ripple current is fairly constant and independent of the load current. At light loads the ripple current will exceed the load current, with the result

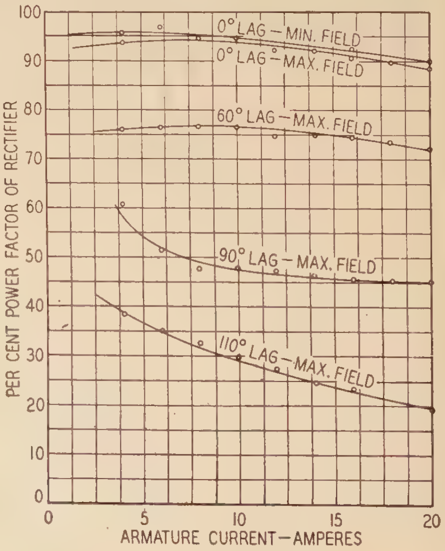


Figure 12. Power-factor curves for a three-phase full-wave rectifier with half-wave phase control. Rectifier used to supply a d-c motor

that the armature current will become intermittent. It is this condition which causes the high ratio of effective to average current at light loads. Fortunately this pulsating armature current does not cause undue motor noise or vibration when the rate of change of armature current is kept within the limit required for satisfactory commutation.

The curves in figure 11 show the variation of speed with load, or armature current. These curves show that the motor has considerable speed regulation largely because of the reactance in the a-c supply lines. When phase control is employed to reduce the motor speed, the speed regulation at light loads is quite large. This is due to the intermittent armature current at light loads. Where less speed regulation is required this may be obtained by using less line reactance or by a number of methods of compounding the rectifier to give a grid-phase shift in response to load. It is undesirable to operate with a very low a-c line resistance because this will increase the harmonic currents present in the a-c supply and lead to more severe fault currents in case of an arc-back.

Power-factor curves are shown in figure 12 for several grid phase angles, selected to reduce the d-c voltage by steps of about 25 per cent. The data for these power-factor curves was taken with 20 per cent reactance in the a-c lines. It is unlikely that a reactance greater than this would be used.

When the rectifier is operating to give full d-c voltage and with about 20 per cent a-c line reactance the power-factor is about 90 per cent with zero grid angle; and this power-factor is maintained even at light loads as may be seen from figure 12.

If the motor speed is reduced by phase control the power-factor of the rectifier is affected quite adversely. At low speed the decrease in power-factor caused by full-wave phase control is even more than that shown in figure 12.

The reduction of power-factor caused by phase control is one of the important reasons for using motor-field control for part of the speed range. It seems desirable to use motor-field control to reduce the speed until the power required by the motor is not greater than half the full-load power at maximum speed. This corresponds to a 50 per cent speed reduction for a constant-torque load and about 20 per cent speed reduction by field control for a variable-torque load such as a fan. If the motor speed is reduced by field control until the motor power is reduced to half its maximum value the reactive and harmonic power required by the motor will never exceed that required at full load.

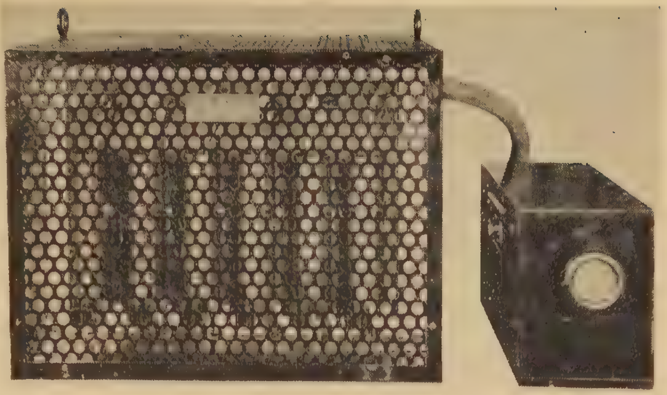


Figure 14. Picture of three-phase full-wave rectifier and associated equipment as used for controlling the speed of a 10-horsepower 1,300-rpm 550-volt d-c motor. One hundred per cent speed range provided, partly by field control and partly by phase control of rectifier

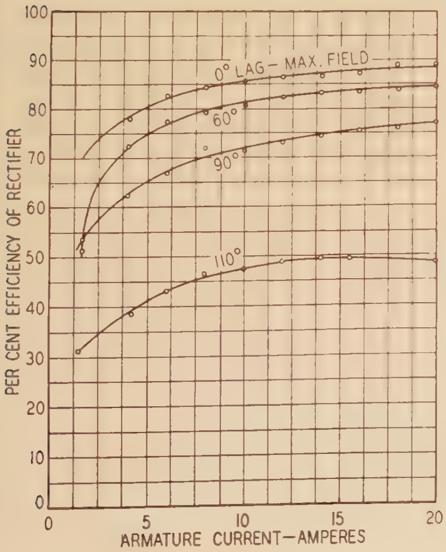


Figure 13. Efficiency curves for a three-phase full-wave rectifier with half-wave phase control. Rectifier used to supply a d-c motor

Efficiency curves are shown in figure 13. These curves are taken for the same conditions of operation as the power-factor curves of figure 12. The efficiency as shown in figure 13 applies to the rectifier only and does not include the motor losses. Since motors may vary considerably in efficiency it seems best to give rectifier efficiency separated from the motor efficiency. The very low efficiencies found at low speeds, result from the fact that the major rectifier loss is caused by the arc drop of the tubes which is approximately a constant voltage drop. As the d-c voltage is reduced by phase control the arc drop represents an increasing proportion of the total power. It should be recognized that the rectifier efficiency will be lower, if a lower a-c supply voltage is employed.

Starting, Reversing, and Braking

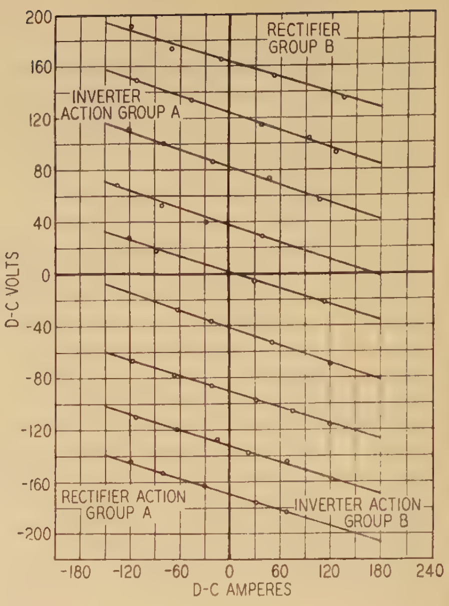
Any means of motor speed control which permits the motor to be operated at very low speeds provides the requirements essential for starting. Phase control of the rectifier gives the control necessary for starting the motor and accelerating it smoothly, without producing abnormal currents. A suitable interlock between the phase-shifting transformer in the grid supply and the contactor in the motor circuit will prevent an improper starting sequence.

If a simple rectifier circuit is employed, the unidirectional conductivity of the rectifier necessitates the reversal of the motor connections, either armature or field, when the motor is to be operated in a reverse direction. Regenerative braking is also impossible when a simple rectifier circuit is used because there can be no reverse current to decelerate the motor. When regenerative braking or rapid reversal of the motor is required a double tube-circuit should be employed as shown below.

D-C Motor Operated From a Reversible Electronic Converter

There are many motor applications which require either rapid reversal or regenerative braking. Elevators and hoists are two examples, typical of the service where deceleration is an essential requirement. For these and many similar applications, a d-c motor operating from a simple phase controlled rectifier, is inadequate as was pointed out above. It is possible, however, to add the regeneration braking feature, by the addition of a duplicate set of tubes connected for reverse current and with their grids excited for inverter operation.

Figure 16. Curves showing the variation of d-c voltage with load current for a reversible electronic converter



REGENERATIVE BRAKING

The circuit diagram in figure 15 shows a double set of tubes with a single-phase a-c supply. One set of tubes is connected for reverse current, which is essential for regenerative braking. The operation may be explained as follows: assume that the *A* group of tubes is rectifying and furnishes current to drive the motor in a clockwise direction. Should the d-c motor be overspeeded a little, the motor counter electromotive force will exceed the rectified voltage and no current can then flow from the rectifier. The *A* tubes are then inoperative.

If the inverter tubes, the *B* group, as shown in figure 15, are properly adjusted a small increase in the counter electromotive force of the motor will be sufficient to cause them to begin inverting. They will then draw power from the motor, causing it to operate as a generator with the corresponding retarding torque. The power delivered by the d-c machine is transferred to the a-c system through the *B* group of tubes acting as inverters.

There is of course some speed regulation with load for both the rectifier and inverter tubes. With rectifier or driving operation, the speed regulation is positive and the motor speed decreases with increasing armature current. For inverter or braking operation, the speed regulation is negative, and the motor speed increases with increasing armature current. The curves shown in figure 16 are typical speed armature-current characteristics as the motor operation is changed from braking to driving.

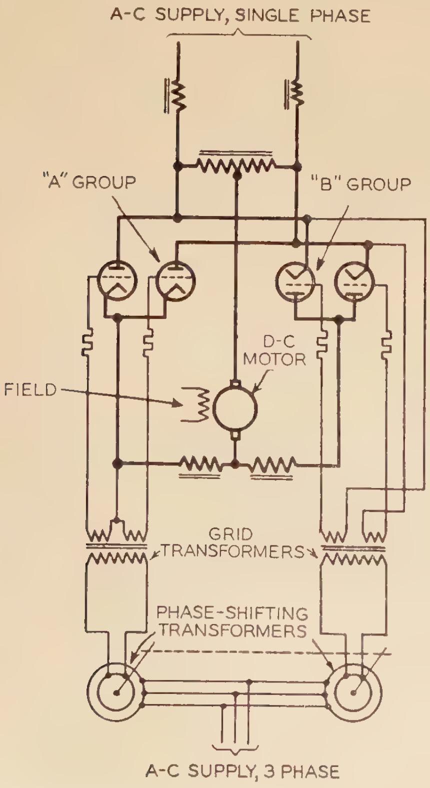


Figure 15. Circuit diagram for a reversible electronic converter for supplying a d-c motor

Reverse Rotation by Phase Control

The action as explained so far would permit the motor to operate at an approximately constant speed over a load range, from full driving to full braking. A constant speed application which requires regenerative braking is, however, seldom if ever encountered. Speed variation and reversal are essential in most applications which require braking. With the circuit arrangement as shown in figure 15 it is possible to vary the motor speed by phase controlling the rectifier and inverter simultaneously. Full-wave phase control is most satisfactory for this service.

When full-wave phase control is employed the rectified voltage is reduced to zero by a grid phase-shift of 90 degrees as is shown in relation (3) and figures 5 and 7. If the grids be retarded still further, the rectifier will be found to have a counter electromotive force and may operate as an inverter. Similarly, advancing the grid phase-angle of an inverter first reduces the counter electromotive force to zero and then produces a forward or rectifier electromotive force.

The grid-control characteristic of a rectifier having full-wave phase control, as shown in figure 7, is shown again in figure 17. In the latter case, however, the operating

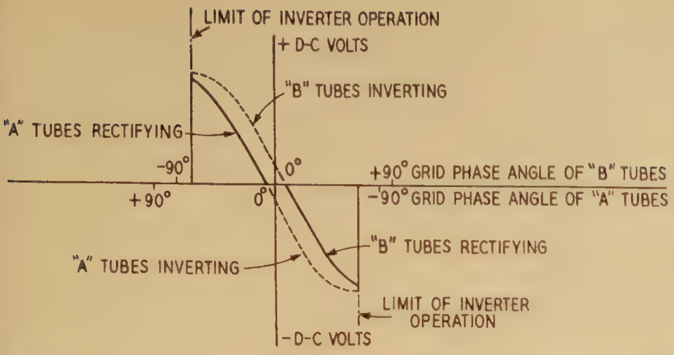


Figure 17. Curves showing the variation of d-c voltage with grid phase angle for a reversible electronic converter

curve of both the *A* and *B* tube groups are shown, and the rectifier phase-control curve is extended to show the inverter range. It is evident from an inspection of figures 15 and 17 that the distinction between inverter and rectifier operation is largely a question of the relative phase of current flow in the a-c circuit. The principal difference arises from the change of the voltage stress across the tube from negative to positive as the operation is changed from rectifying to inverting. The positive tube voltage in the inverter region necessitates a negative grid bias during the entire non-conducting interval. Assuming a suitable grid excitation, however, a group of tubes will function as either a rectifier or inverter. Such a tube group is conveniently and accurately described as a converter.

When the tube converter employs natural or phase commutation, its operating range covers only about 180 electrical degrees. Phase control as a rectifier is then possible only by retarding the phase of the grids. There is a commutating voltage in inverter operation only if the current transfer takes place before the voltage of the incoming phase equals the voltage of the outgoing phase. Fortunately the rectifier and inverter quadrants are adjacent and we may pass from rectifier to inverter action or conversely by a continuous shift of the grid phase-angle.

If the d-c voltage of a rectifier is to be reduced, the grids of the rectifier tubes should be retarded. The opposite is true for an inverter, and the grids of the inverter tubes should be advanced to reduce the operating voltage.

For this reason separate phase-shifting transformers are required for the *A* and *B* tube converters. These two phase-shifting transformers may however be rigidly coupled and moved simultaneously if they are so arranged that the electrical rotation of one is opposite to the other. This is indicated on figure 17 by showing reversed scales for the grid phase-angle of the two converters.

If the phase control characteristic of the *A* and *B* converters are displaced as shown in figure 17, the operating voltage of the inverter will exceed the rectifier voltage for both directions of rotation and there will be a "discrepancy" or change in motor speed when changing from driving to braking. This phenomena can be eliminated by proper alignment of the two phase-shifting transformers. Should the inverter be set for an operating voltage below the rectifier voltage, there will be a circulating current between the rectifier and inverter and corresponding losses. A small circulating current is desirable when a motor speed "discrepancy" between driving and braking is objectionable.

When the phase-shifting transformers are displaced beyond the safe operating limits the tubes acting as inverters lose their commutating voltage. This results in a short circuit between the two converter groups, and should therefore be avoided.

With a circuit arrangement as shown in figure 15 and suitable grid excitation for both the *A* and *B* converters, as discussed above, the motor speed can be controlled through a speed range from full speed forward to full speed reverse. The control required is only a movement of the phase-shifting transformer. At all speeds, forward and reverse, the motor will give regenerative breaking if over-speeded. With the phase-shifting transformers in any operating position there is a speed armature-current characteristic, similar to those shown in figure 16.

The combination of d-c motor and reversible converter just described, is quite flexible and has a very sensitive control in the phase-shifting transformers. This arrangement appears suitable for many applications which have formerly required a Ward Leonard set.

Torque Amplifier

The sensitive and accurate control permitted in the grid circuit of the converters of the motor just described adapt

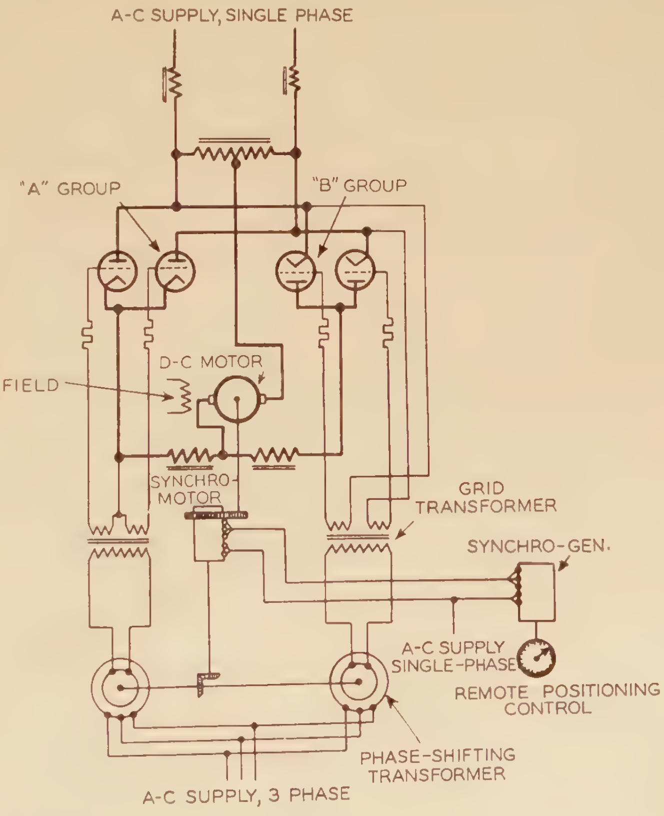


Figure 18. Functional diagram for a torque amplifier employing a d-c motor and a reversible electronic converter

it to many applications not adequately served by a Ward Leonard combination. The arrangement shown in figure 18 gives a scheme for producing a torque amplifier or positioning device. The only change required from the circuit of figure 15 is that the two phase-shifting transformers, which supply the grid power are not manually operated as in figure 15, but are connected to both the positioning control and the main motor, in effect, as through a differential. Referring to figure 18, a displacement of the positioning control acts through the synchro-motor to cause a movement of the grid phase-shifting transformers. This grid shift sets up a current causing the main motor to move. The main motor is connected to the stator of the synchro-motor through a gear. The rotation is such that a movement of the main motor produces a phase shift which cuts off the current causing the motor to move. Therefore, when the main motor has moved through an angular displacement corresponding to the displacement of the position control, the main motor will have corrected the grid phase-displacement which was caused by the movement of the positioning control. In this manner the main motor is kept in close correspondence with the positioning control. If the controlling device is kept in continuous motion, the motor is compelled to follow in a corresponding angular position, but the load or torque burden on the positioning control is only a slight portion of the torque exerted by the main motor in driving its load. The grid control is so accurate and rapid that very close correspondence is maintained between the motor shaft and the positioning device. Automatic tools offer an attractive field of application for a reversible electronic converter arranged to operate as a torque amplifier or position control.

Conclusions

Three different arrangements have been described, each employing electronic devices for controlling the speed of a motor operating from an a-c power supply: viz., the synchronous motor using thyratrons as a commutator (see references 1, 2, 3, 4), the wound-rotor induction motor using a rectifier and d-c motor on the secondary, and a phase-controlled rectifier supplying a d-c motor from an a-c power source. These three schemes all have attractive features and each type of motor will probably find a field of application.

The simple phase-controlled rectifier supplying a d-c motor may use a number of rectifier circuits other than the three-phase full-wave circuit described. For small motors a single-phase rectifier is adequate. The combination of a d-c motor and a simple phase-controlled rectifier provides a very flexible motor operating from an a-c source of power. It is simple and has a high apparatus economy. This motor should find a wide field of application in small and moderate sizes.

If the service demands regenerative braking this feature may be secured by adding a duplicate set of tubes, and the grid excitation necessary to produce a reversible electronic converter.

The combination of d-c motor and reversible converter, may be employed not only as a reversible variable-speed drive but with suitable phase-shifting transformers, it may be used as a torque amplifier or positioning device. As a torque amplifier this arrangement has high precision, and rapid response. For many problems it offers a solution unequaled in accuracy and elegance.

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Discussion

E. F. W. Alexanderson (General Electric Company, Schenectady, N. Y.): Our paper has the object of indicating some of the many possible applications of electron tubes for power transformation. Specifically, it deals with the controlled rectifier, inverter and frequency changer as a power supply for motors. It has not been possible to include in this discussion all the combinations that we have in mind. There is, for instance, one combination which we should like to include and which recent tests indicate to be one of the most promising. This is to absorb the secondary power of the induction motor in a thyratron frequency changer and return the energy to power lines. This combination requires eight tubes if a quarter-phase motor secondary is used.

At this stage is may be interesting to forecast how high motor powers may be conveniently operated by such methods. We may assume that tubes of 200 amperes average capacity will be available. It may also be assumed that the induction motor secondary is wound for 2,300 volts. Such a combination will control a motor of 4,500 horsepower. In this electronic technique we are by the nature of the problem compelled to analyze our expectations for the near future even though the ways and means to meet them are not available for the moment. There is a good reason for this. The basis for this work is the electron tube itself around which all the rest of the apparatus must be designed. But a development of high-power electron tubes is a long and expensive process. To furnish the incentive for this, it is necessary that the electrical engineers who deal with power problems both in design and operation should analyze their needs so that they will be able to point out the directions in which such development will show economic advantages. We hope that a discussion of the subject by the Institute will serve this purpose.

C. C. Shutt (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors present an interesting and timely paper on the subject of electronic speed control. It is of particular interest to note that the authors have given considerable space to the wound-rotor type of machine with secondary control. For several years the writer has considered this arrangement preferable to the authors' earlier schemes, which used primary frequency control and a synchronous-type motor, for the following reasons:

1. The number of tubes is reduced and their connections simplified. Only one electronic power conversion required when d-c machine is used as described.
2. A practically standard motor is used with normal densities in copper and iron.
3. At reduced speeds the power factor can be practically as good as with resistance control.
4. Unless the speed reduction is large, the kilowatt rating of the tubes is reduced by the use of secondary control.

With these features in mind, a 350-horsepower unit has been built, which was designed primarily for a fan drive. It uses grid control on the tubes for the lower portion of the speed range. The advantage of grid control for such a drive is that the reduction of the d-c voltage reduces the flux required in the d-c motor at the lower speeds, and thus reduces the size of this machine. It will be recognized that this reduction of d-c voltage is accompanied by an increase in direct current and the current in the secondary of the induction motor. But, with a fan type drive, the current is still well below the rating of the windings at the low speeds. The use of grid control causes a reduction of primary power factor at low speed. But this is not objectionable at light loads which accompany low speeds on a fan drive.

A 1,250-horsepower, 1,200-rpm unit is now under construction.

In common with a Kramer drive, and other forms of secondary control, the drive will develop a maximum of practically constant horsepower when the secondary power is recovered in a d-c motor on the main shaft. It will develop a maximum of practically constant torque when the secondary power is recovered by some other means. These statements assume that the induction motor is worked at normal flux and current densities at all speeds. The equations 1 and 2 of the authors' paper appear to be based on this assumption.

Attention is called to the second sentence of the section under "Apparatus Economy." The authors state "The rating of the rectifier must approximately equal that of the induction motor." This statement is also based on the same assumptions as equations 1 and 2, the correctness of which depends upon whether the tubes are rated in current or kilowatts. Under the authors' assumptions, the tube current is constant regardless of the speed. Neglecting grid control —and it would probably not be used under these assumptions—the d-c voltage increases as the speed decreases. Hence, the kilowatt rating of the tubes is a function of the speed reduction, and certain types of tubes have higher current rating at reduced voltage. Hence, smaller tubes can be used with limited speed reduction.

In closing, the writer would point out that the relatively simple circuit consisting of an induction motor with a rectifier and d-c machine in the secondary only scratches the surface of the possibilities of this type of variable speed drive. Other types of electronic secondary control have been investigated for a range of applications and will be presented in the near future.

L. A. Kilgore (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): This paper gives a good description of several circuits which may be used for a-c variable-speed drives employing electronic tubes, but the description of the motor requirements is confusing at certain points. Equations are given for the relation between d-c and a-c motor ratings. These equations are misleading because they are only applicable to one special type of load, but which special case they are intended to cover is not stated.

Under the heading of "Apparatus Economy" the ratio of d-c motor rating to a-c motor rating is given in equation 1 as: the ratio of maximum to minimum speed minus one, for the case of a d-c motor connected to the same shaft as the a-c motor. This relation would only be true for the special case of constant power; also the ratings would have to be based on the minimum speed.

Also equation 2, which applies to the case where the secondary power is fed through a rectifier to a d-c motor of a motor generator set, is only applicable to the case of constant power; furthermore, it would seem that a maximum speed equal to synchronous speed had been assumed.

The general idea of a rectifier applied to the secondary of a wound-rotor motor to furnish power either to a d-c motor on the same shaft or to be fed back into the line is old, but very little use has been made of it in the past. However, with the recently developed thyratron and ignitron tubes, this type of variable-speed drive holds real promise. One place where it is particularly applicable is in the drive of large fans. For this case, smooth speed control from zero to 90 per cent of synchronous speed is possible with a d-c motor rated only about 40 per cent of the total power required at full speed, and for ignitrons the rectifier rating would be approximately 60 per cent of the maximum power output if the capacity is based on the increased voltage rating at low speeds.

Grid-controlled rectifiers have been used for some time for the purpose of speed control of d-c motors with or without the use of field control of the motor. The authors put particular emphasis on the full-wave three-phase circuit, which avoids the use of a transformer when a suitable a-c voltage source is available. Besides the advantages mentioned by the authors, this circuit has the additional advantage where the blocking of grids or ignitor circuits may be used to interrupt the a-c supply to an arcback, for unless a tube in both groups arcs back at the same time, there will be no back feed from the d-c motor.

The authors show some improvement in power factor at low d-c voltages for the particular arrangement which they call half-wave phase control of the full wave rectifier. However, this is accomplished at the expense of an increase of the magnitude of, and the introduction of, lower frequency components in the d-c voltage ripple. It may be found that where improvement in power factor is desired, it can be obtained more economically some other way.

J. H. Cox (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): This paper constitutes a *review of several methods* of controlling the speed of motors by electronic means, and as such is a valuable contribution. However, since the paper *mentions only thyratrons* as the electronic device to be used, and since thyratrons are only practical in relatively small sizes, the inference is left that this method of speed control is only applicable in small capacities. *Actually, the group with which I am associated* has carried out tests with a 350-horsepower drive using a similar method of control and is now building a 1,250-horsepower drive.

Throughout the paper the authors' choose the *three-phase full-wave circuit* and this circuit is much more convenient for this application than the more conventional power rectifier circuits, though the latter are somewhat more efficient. However, the three-phase full-wave circuit demands that the *cathodes associated with at least three* of the anodes be separated from the others and *there are serious objections* to building the conventional metal tank rectifier in single-anode tanks. However, *ignitrons are normally built in single-anode units*, and where no vacuum pumps are required they are amenable to any electrical circuit desired. Therefore, the methods of speed control described by the authors are now conveniently available up to sizes requiring electronic power that can now be provided by ignitrons with sealed-off construction. As mentioned in Mr. Kilgore's discussion, for a blower type of load, the electronic capacity required is only 60 per cent of the maximum power output at maximum speed.

W. R. King (nonmember; General Electric Company, Schenectady, N. Y.): I am particularly interested in the system described by the authors for controlling the speed of a d-c motor by means of a phase-controlled rectifier. I have had some experience in applying electronic equipment to the control of d-c motors and in the past have been forced to conclude that, primarily for economic reasons, the electronic systems were limited to the field of applications where some very special motor-control functions were required. Numerous successful applications have been made but practically all have been to problems extremely difficult if not impossible to solve by more conventional means.

However the new system described by the authors holds promise for obtaining with reasonable economy the advantages of adjustable speed motor operation where only alternating current is available. Thus it opens to the electronic control the field of applications in which the problem is merely to obtain adjustment of motor speed, rather than to obtain some special and more or less automatic control.

The system provides not only a source of direct current for operation and control of the motor by the conventional field rheostat method, but also an adjustable armature voltage. The wide speed range thus afforded makes it applicable to drives requiring a wider range than the conventional three-to-one or four-to-one adjustable-speed d-c motor. I believe this will make the system quite useful in certain machine tool applications, where greatly reduced speeds are sometimes needed.

For machine-tool application, the system provides one distinct advantage over the use of a motor generator set and exciter. This is that the equipment can be built up into a small cabinet which can be mounted directly on or in the machine in the same manner that magnetic controllers are now mounted. This is quite important in view of the decided trend toward making machine tools completely self-contained so that they may be readily moved for new production setups. Against this advantage, of course, is the fact that user must consider the cost of occasional tube replacements.

The armature current-motor-speed curves in the authors' figure 11 show a regulation at reduced speed which may be excessive for some applications. I do not believe that the slope of the main part of the curves will be excessive for most applications but the large increase in speed at very light loads may be objectionable. Individual applications would have to be studied to determine the suitability of the system in this respect. As the authors point out, the regulation may be improved by various compounding methods but of course this will complicate the system to some extent and one of the big economic advantages of the system is its inherent simplicity.

One other disadvantage, inherent to the simple rectifier systems, is that regenerative braking cannot be obtained without a very substantial increase in the cost and complexity of the equipment. For some applications only rapid braking is required and in such cases dynamic braking can be obtained by addition of suitable braking resistor and magnetic control. However, other applications require rapid deceleration to a reduced operating speed and the method of obtaining this operation automatically is more complex.

Although it is true that the system as described may be used to start the motor from rest without additional magnetic control, I believe that there may be some objection to this arrangement, particularly on machine tools in the high production industries. It would be difficult to educate the operators to accelerate the motor at a proper rate by turning a control knob when they have already been educated to push a button and obtain acceleration at the proper rate automatically.

In general, though, this new system is a distinct forward step and I believe numerous applications for it will be found.

C. H. Willis: The authors appreciate the interest shown in their paper by those giving discussions. It is evident from this wide interest that electronic devices may find a wide field of application in motor control. It is to be hoped that this field will develop rapidly.

In some of the discussions there appears to be a divergence of opinion as to the rating of the control equipment, where a rectifier and d-c motor are used to control the speed of a wound-rotor induction motor. Since this equipment is required to carry a maximum current under one condition of operation and also must produce a maximum voltage under some other condition, the authors believe that the proper rating is the product of the maximum current and voltage. While the control equipment may not operate at this rated load it must be capable of so operating and this rating gives the most accurate and conservative estimate of the apparatus.

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following three pages appear discussions submitted for publication, and approved by the technical committees, on previously published papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

The PCC Street Car

Discussion of a paper by C. F. Hirshfeld published on pages 61–6, of this volume (February section) and presented for oral discussion at the modern electric vehicles session of the winter convention, New York, N. Y., January 24, 1938.

E. J. Allen (General Electric Company, Pittsfield, Mass.): The author is to be commended for his description of the salient features of the modern Presidents' Conference Committee street cars, over 500 of which have been in operation during the past three years. Low operating cost and low maintenance expense to the transit company is obtained through applied research and careful design, yet securing modern appearance, speed consistent with good riding quality, good illumination, and ventilation.

The PCC street car, like its earlier predecessors, derives its motive power from overhead trolley lines, which are very frequently exposed to lightning, even in urban areas. Consistent with the objectives of low first cost, and low maintenance expense in general design of the PCC car, a d-c capacitor-type lightning arrester is installed in one of the compartments. To meet the demand for a d-c lightning arrester, which does not require maintenance and one that is unaffected by winter and summer temperatures, the d-c capacitor type arrester has been made possible only through successful research in dielectrics during the past few years.

Figure 1*a* shows a type of 750-volt four-microfarad d-c capacitor arrester which has been used on PCC cars. Another d-c capacitor-type arrester having the same electrical characteristics, but enclosed in a drawn steel housing, is shown in figure 1*b*.

This arrester is directly connected between positive trolley and car frame, and depends entirely upon the effect of a large amount of capacitance for its impulse protective characteristics. While the protective voltage maintained by the capacitor-type arrester depends on the wave shape and amplitude of the impulses applied on the trolley circuit, this protective level is only 3,000–4,000 volts crest for typical applied waves on trolleys supported by cross spans on steel or guyed wood poles. Moreover, the sloping of applied impulse wave front accomplished by the capacitor-type arrester is essential in order to reduce the turn-to-turn impulse stresses in the motors and car equipment.

The protective characteristics afforded by d-c capacitor arresters as shown by calculation and tests are rapidly being substantiated in service by the virtual lack of lightning failures reported on PCC car equipments.

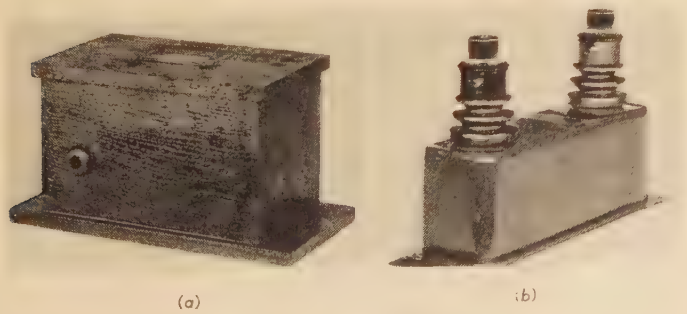

(*a*) (*b*)

Figure 1. Typical d-c capacitor-type lightning arresters for 600-volt d-c service

W. I. Rodgers, Jr. (nonmember, Brooklyn and Queens Transit Corporation, Brooklyn, N. Y.): In Brooklyn, the Presidents' Conference Committee car was first introduced to the riding public. The 100 new cars replaced old equipment on four lines starting October 1, 1936. New schedules were written, headways reduced, and an improved service resulted. Rider endorsement followed quickly and the mails brought hundreds of appreciative comments.

To date, the cars have operated over five million miles. Comparing this with average mileages for older equipment we find that the new cars have traversed one-third more mileage over equal periods. As these cars are able to do more work per day, it follows that operation costs are lowered.

Much of the electrical and the mechanical equipment of the cars had been tested in Brooklyn on the widely known "million dollar" experimental car. Many more improvements were selected for the production cars. Fundamentals had been well established by the PCC research group. It remained for actual service operations on a wide scale to prove the equipment. The early experiences in Brooklyn with the first production cars from the factory quickly brought out the necessity for changes of slight importance in themselves but highly desirable for maintenance reasons. Both construction and engineering detail reflected the careful planning and long research to provide a modern vehicle that could be priced attractively to operating companies.

In the desire to build such a vehicle to these standards, no sacrifice of sturdy, dependable equipment and accessories was permitted. Thus, our operating difficulties have been minor and have not in any way interfered with smooth, successful performance during the year.

Our maintenance costs have not yet reached their level because of the changes and improvements applied after the delivery of the cars. It is confidently expected that costs will shortly match the system average and ultimately be less than the costs of maintaining the conventional street car of former days.

Reduced track costs are anticipated by the use of the resilient wheels and much elimination of the hammer-blow pounding of steel wheels on the rail seems assured. All lateral movement and swing of the car body is well controlled by the rubber coned springs at the four corners of the trucks and the body swing links. These design factors should go far toward reducing destructive forces which cause excessive track maintenance.

Coupling Between Parallel Earth-Return Circuits Under D-C Transient Conditions

Discussion and author's closure of a paper by K. E. Gould published on pages 1159–64 of volume 56, 1937, AIEE TRANSACTIONS (September 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the communications session of the winter convention, New York, N. Y., January 24–28, 1938.

G. Wascheck (Bell Telephone Laboratories, Inc., New York, N. Y.): Experimental measurements made in connection with the d-c transient induction tests presented in Mr. Gould's paper afforded opportunities for studying certain aspects of the problem of determining local earth resistivities and structures—which problem is an important one in predicting the a-c coupling between earth-return circuits. If the earth were uniform, such resistivity would be independent of separation or frequency. If the earth were not uniform but varied as some function of the depth, the resistivity would vary with frequency because of the lesser penetration of the current to the lower depths and the increased concentration closer to the surface as the frequency is increased—a phenomenon closely allied to that of skin effect with which we are all familiar as applied to metallic conductors. This is also reflected in a change of the in-phase and quadrature components of the coupling from that of a uniform earth structure. Thus, a series of tests over a large frequency range would show variations in the resistivity indicated at the surface which would be a function of the depth, and from which interpretations of the structure may be made—provided, of course, that such variations are roughly in a horizontal plane and not too deeply submerged for the frequencies employed. The resistivity indicated at the lower frequencies and hence influenced by the resistivity of the lower depths is not necessarily the actual resistivity at the lower levels but rather a composite of the entire cross section of the area through which the current is distributed. Therefore, whereas the trend will qualitatively indicate resistivity variations, comparisons with theoretical calculations for simple structures are required in order to determine the nearest equivalent structure.

For example, from the Jennings, La., test results, a curve of resistivity based on the magnitude of the mutual impedance (differing slightly from the curves in figure 13 of the paper, which are based upon the reactive component of the mutual impedance) was plotted against frequency, and indicated variations as follows: a resistivity of about 15 meter-ohms at 20 cycles, increasing to over 30 meter-ohms at 100 cycles, and then decreasing eventually to about ten meter-ohms at 3,200 cycles. Calculations show that this trend may be explained on the basis of a horizontally stratified earth, and geological studies substantiate the existence of such a structure in this region, which is in the so-called delta country around the mouth of the Mississippi River. This area has been built up by the deposition of silt over a great number of years and is probably quite uniform in a horizontal plane. In addition, experimental results were available, of resistivity measurements made in a 2,000-foot oil well a few miles distant, which indicated a surface layer over a hundred feet thick of rather low resistivity, a second layer below this several hundred feet thick with a resistivity about three to four times as high, and below this a gradual change to a very low resistivity, which low value is no doubt due to the salt water which underlies this territory.

A simpler method for determining earth resistivity and structure, requiring less time and apparatus than the a-c tests and easily analyzed when the structure is not too complex, is that employing direct current. Such tests were also made at this site and comparisons with the above results indicated a close correlation with the general resistivity trend and structure.

The d-c procedure, which has been used for some time in detecting variations in the earth's structure, particularly in geophysical prospecting work, consists in applying direct current (periodically reversed through a commutator to reduce polarization and stray voltage effects) to a pair of ground electrodes, called the current electrodes, and measuring the potential between two intermediate electrodes, called potential electrodes. This determines the mutual resistance between the two circuits from which, with the known geometrical arrangement of electrodes, the apparent uniform earth resistivity may be determined directly by a simple formula. To determine possible variations of resistivity with depth, use is made of the fact that the direct current penetration into the earth becomes progressively greater as the spacing between the electrodes is increased. When these variations with spacing assume certain definite trends, calculation and tests on small models have shown that a fairly reliable interpretation of the structure may be made. The tests at Jennings, which were made with current electrode spacings from a few feet up to nearly 10,000 feet indicated a resistivity of little over ten meter-ohms at the closer spacings which increased to 35 meter-ohms at the intermediate spacings and then dropped off rapidly at the last measured point, indicating about six meter-ohms with the trend still downward. These results agree essentially with the oil well data and with the a-c results, where a continuation of the measurements below 20 cycles quite likely would have shown a progressive drop in resistivity to the d-c value for a very wide spacing of electrodes.

Thus, provided the coupling characteristics for the resultant structure are known, or an equivalent earth resistivity can be substituted for it at a given frequency, results from d-c exploration tests enable a close estimate to be made of the a-c coupling. Tests in many places have indicated that where the structure is not too complex, an equivalent uniform or a two-layer stratified structure may be postulated from d-c exploration data, and for these cases the variations of coupling with separation can readily be calculated. More complex structures may often be reduced to a simpler structure, though invariably in heterogeneous territory, irregularities in a horizontal direction are also present. These introduce difficulties in assigning an average resistivity, especially for a long circuit, when only exploratory or sampling measurements are made. This is true when measurements are made either by the a-c or d-c method and a larger portion of the territory must be explored. However, where sampling methods are deemed satisfactory, the d-c procedure provides a useful method for predicting a-c coupling between earth-return circuits.

A New Single-Channel Carrier Telephone System

Discussion and authors' closure of a paper by H. J. Fisher, M. L. Almquist, and R. H. Mills published on pages 25–33 of this volume (January section) and presented for oral discussion at the communications session the winter convention, New York, N. Y., January 24–28, 1938.

Glen Ireland (American Telephone and Telegraph Company, New York, N. Y.): The members of the Institute may be interested in some brief comments regarding the application of the type-*H* system in the Bell System plant.

About 35 type-*H* systems have been placed in commercial service and engineering has been completed on a great many more. Some of the systems are being applied for distances as short as 25 miles, others are being used for distances up to 160 miles. In the engineering of these systems, the small size of the *H* terminals is being found to be of considerable advantage particularly in offices where floor space is at a premium. In the case of one office it was possible to defer the enlargement or rearrangement of the toll terminal room and at the same time take care of the toll circuit growth by removing three low bays containing three type-*D* terminals and in their place installing two low bays containing 4 type-H terminals. The type-D terminals are to be reinstalled elsewhere where floor space is not a controlling factor.

Experience with the *H* systems already in service although limited, has been very satisfactory. The circuits are providing good quality, are very quiet and relatively stable. The systems are simple and easy to maintain, relatively few routine maintenance tests being required. In particular the use of varistors as the modulating and demodulating elements is helpful since it results in greater freedom from carrier leak and avoids the tests and adjustments of carrier leak required rather frequently in the case of previous types of systems employing vacuum tubes.

E. E. George (Tennessee Electric Power Company, Chattanooga): In October 1937 The Tennessee Electric Power Company leased from Southern Bell Telephone and Telegraph Company a type-*H* carrier system for use over the power company owned telephone line between Nashville and Chattanooga. This carrier system has provided one of the finest talking channels that we have ever used. The quality and volume are above the levels on the best toll circuits and the noise level is almost zero. This latter point is particularly remarkable in view of the fact that the power company telephone line over which this channel operates is "a hot telephone line" for most of its length. This telephone line consists of 165 miles of open wire of which 85 miles are on the same right-of-way as 110-kv transmission line. The line has several way stations with the usual drainage coils and insulating transformers. A portion of this circuit constitutes the side leg of a phantom with mid-tapped insulating transformers used for phantom coils. At one end there is a few hundred feet of entrance cable.

During the installation of the type-H carrier channel it was assumed that the two insulating transformers in the main line would have to be by-passed with high voltage condensers but it was found possible to operate without by-passes provided the ringing gain was increased sufficiently. By-passing insulating phantom transformers was found to make the phantom circuit useless due to the effect of the condensers in transmitting longitudinal noise frequencies. The circuit has been operating satisfactorily several months with one insulating transformer by-passed and one without by-pass.

The line has several way stations and the only changes made at these stations were to install small low pass filters ahead of the subsets on the station side of the connecting key or cord circuit. These filters are thus normally kept off of the line.

At present the power supply for the carrier terminals is derived from 115 volts a c although 130 volts d-c is available near by. For communication under emergency conditions such as dispatching, it would be highly desirable if the equipment could be modified to work off 130 volts d-c with no intermediate taps and no separate 24-volt battery. When the installation was first made some of the way station filters were omitted temporarily. Although the use of the voice channel created noise on the carrier channel and vice versa, the modulation was apparently inverted and the crosstalk was unintelligible. For this reason filters have been omitted at the patrol booth stations which are seldom used.

To power engineers familiar with the usual weaknesses of copper oxide rectifiers in the matter of heating, aging, overloading, etc., it seems remarkable that rectifiers have been found to be satisfactory as modulators and detectors in a high grade communication circuit. Elsewhere it has been stated that in some respects the copper oxide rectifier is superior to the vacuum tube for such purposes and it would be interesting to hear the authors of this paper discuss this factor in a little more detail. As noted the space requirements of the new "H" terminal are small, and its low cost makes it very attractive to power companies and others even on relatively short telephone lines. A type "H" carrier terminal has recently been installed by a neighboring company over a 20 mile telephone circuit on power line right-of-way where rectifier noise made the voice frequency circuit unusable. The channel has been so satisfactory that a second one is being installed.

J. E. Smith (nonmember; RCA Communications, Inc., New York, N. Y.): During his presentation Mr. Almquist stated that ten copper-oxide disks were series connected in each branch of the modulator bridge arm. Was the multiple-disk varistor used to permit high-signal-level inputs, and, if so, what was the maximum signal level?

M. L. Almquist: Mr. George suggested that some further discussion of the advantages of copper-oxide varistors over vacuum tubes as modulators and demodulators would be of interest. The principal advantages are better balance, greater stability, lower cost, smaller size, and reduced power consumption. The modulator circuit in the type-H system consists of a copper-oxide varistor and a single tube amplifier. To accomplish the same result with vacuum tubes would require the use of three tubes, two tubes operating as a single-balanced modulator and one tube operating as an amplifier. In order to obtain a good balance in the vacuum-tube modulator, which is necessary in order to reduce carrier leak and unwanted modulation products, it is frequently necessary to select pairs of tubes whose characteristics closely match each other. The balance will change as the tubes age and will also vary with changes in the power supply voltages. The copper-oxide varistor as manufactured has a balance which is better than can be obtained with vacuum tubes and this balance is maintained over long periods of time, thus avoiding the periodic rebalancing which is required when vacuum tubes are employed. Furthermore, with a double-balanced modulator such as is used in the type-H system, the input frequency does not appear in the output and this simplifies the filter requirements.

In reply to Mr. Smith's question, the primary purpose of using a multiple disk varistor is that it affords an economical way of obtaining units which are uniform in their performance, well balanced, and stable with time. The load-carrying capacity is determined largely by the amount of carrier which is applied; in order to obtain good performance, the carrier voltage across each disk must be larger than the speech voltage peaks at the same point. In this system, the modulator operates at a level which is four decibels below and the demodulator at a level 13 decibels below that at the toll switchboard. The power which can be carried by the modulator without noticeable distortion is of the order of five to ten milliwatts.

A System of Electric Remote-Control Accounting

Discussion and author's closure of a paper by L. F. Woodruff published on pages 78–87 of this volume (February section), and presented for oral discussion at the communications session of the winter convention, New York, N. Y., January 24–28, 1938.

E. R. C. Coe (The National Cash Register Company, Dayton, Ohio): I should like to ask Mr. Woodruff how a customer would identify himself in the event of a lost "charge token." It would seem that permission to set up the account number by hand at the sales counter somewhat destroys the safety of the system.

A. B. Smith (Associated Electric Laboratories, Inc., Chicago, Ill.): This paper deals with the general structure and operation of a system of accounting which is a combination of mechanical and electrical devices. In harmony with the scope of the paper, the author does not treat of these devices.

The business man of today has been fully acquainted with complicated mechanical devices, and he has learned to depend upon them to a very large extent. Beginning with the typewriter, he has been led on to the use of simple adding machines, and from them to the more capable machines like the Comptometer and the several calculating machines. As to their essential functions they are purely mechanical, and though he does not know what is in them, the business man has learned to rely on them. His confidence is justified.

In the accounting system described in this paper, there is the added element of many electrical circuits and devices. The business man may rightly ask, "To what extent are these electrical devices reliable, and what will their failure do to me?"

As most electrical engineers know, for many years the railroads have been using block systems for the safety and expedition of trains. They have made increasing use of interlocking plants to control switches, derails, and signals intersections. In all of these electrical appliances, the circuits are so designed that any failure will result in such a signal aspect as to give a more restrictive indication. Each failure is on the side of safety.

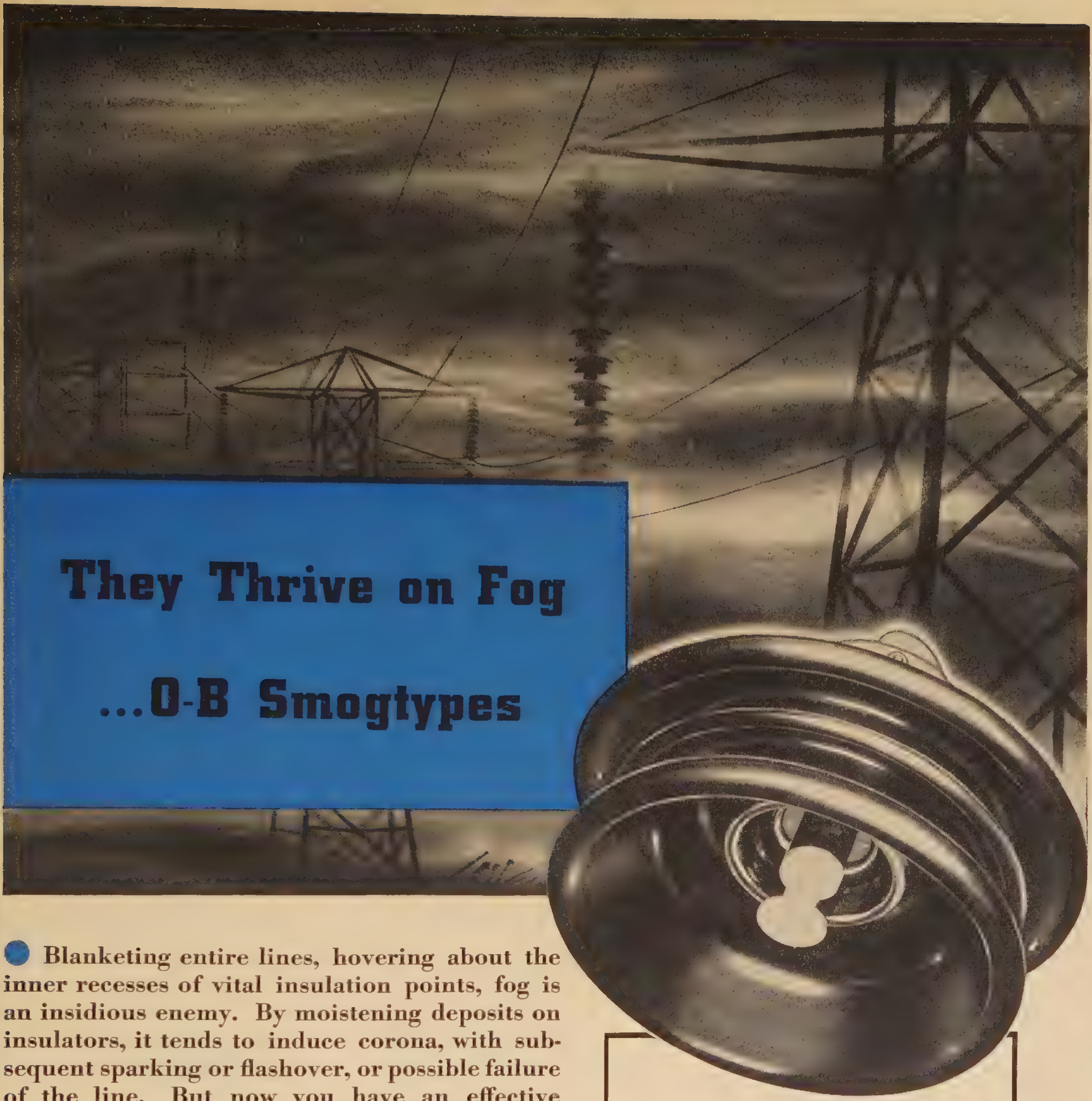
In the case of this electrical accounting, it is of interest to the prospective user to know if similar safeguards exist. He will also like to know the frequency with which electrical faults actually occur, or may be expected to occur. Experience with automatic switching of telephone lines has revealed the high degree of accuracy and dependability which relays and magnets can furnish.

L. F. Woodruff: Doctor Smith's remarks touch on a most pertinent aspect of the system, and one which has been of foremost importance in the development of the individual machines and circuits. This is primarily the elimination of possible error in transmission, and secondarily, the assurance of continuity of operation.

Twin contacts in parallel are used on all circuits. Contacts through the holes in the tags at the transmitter are made at two points. The coding of the numbers to be transmitted has been selected so that just two holes comprise the code for each digit. A contact failure, or an extra hole, will result not in an erroneous transmission, but the control circuits have been designed so that this event would cause a stoppage of transmission. The record would be incomplete, and the price tag would not be stamped. The transmitter would remain locked, and would have to be released by a special key. The record would have to be transmitted over again. If the transmitter were actually defective it would of course have to be replaced.

Mr. Coe has asked how a customer would identify himself in the event of a lost charge token. I agree with his point that setting up the number by hand at the sales counter would somewhat reduce the safety of the system, and we do not recommend that method. We advocate providing at a service station on each floor a place where the customer, upon proper identification, can be provided with a temporary token, good for that day only. A duplicate of this token would be filed for use in making correction in event an error was made in punching.

There are other possibilities for handling this problem, and the final choice must rest with the store management.



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* Smog: A blend of smoke and fog.—*Webster.*

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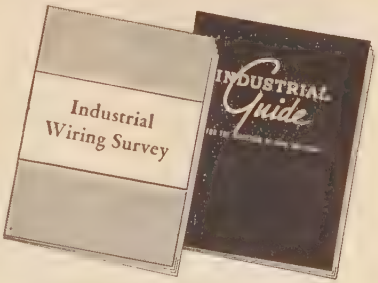

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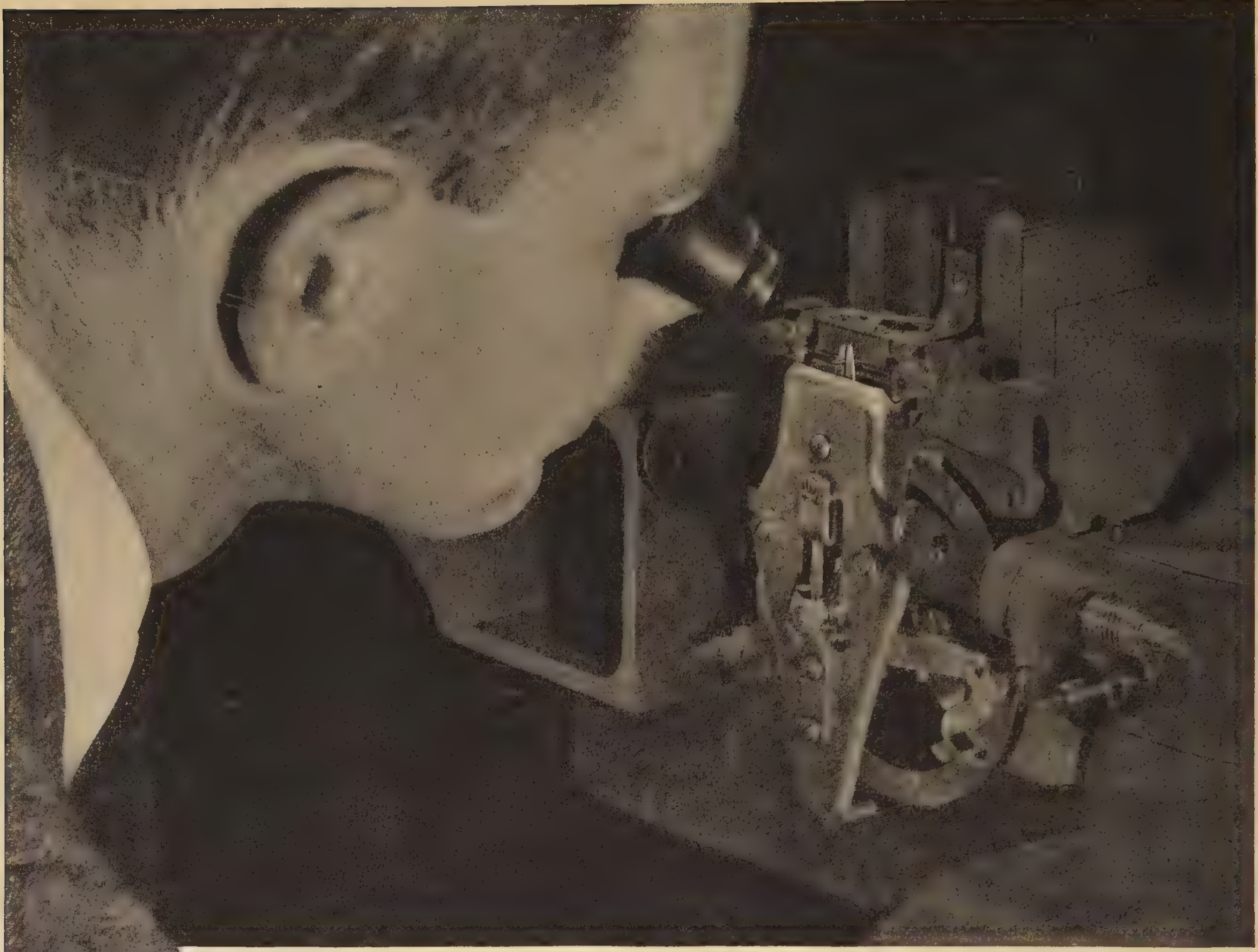

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Industrial Notes

Allis-Chalmers Billings.—For the first quarter this year the Allis-Chalmers Manufacturing Company reports billings of $20,310,099 compared to $17,788,395 for the same months in 1937. Orders booked for the first quarter totalled $19,314,557 as against $24,205,565 for the same months last year. Unfilled orders on March 31 totalled $20,248,025 as against $20,235,507 a year ago.

Radio Equipment for Air Ways.—The first of 44 radio range stations built for the Department of Commerce by the Westinghouse Electric & Mfg. Co. will be installed at Allentown, Pa. The installations all will be made on regular established air routes and will be located in some 20 states. In addition to the complete equipment and installation of the 44 radio range stations, Westinghouse is supplying 50 single transmitter equipments which are to replace present obsolete units. The radio range station equipment supplied for each installation includes everything except the antenna towers and the main building to house the equipment. The principal items of the equipment are the transmitter unit, the coupling unit and the antenna tuning units. The transmitter unit transmits both voice signals and radio range signals. These can be transmitted simultaneously which is not true of the system in general use at the present time. Now it is necessary to interrupt the range signals for the period of time that the weather broadcast is being transmitted.

General Cable Moves Chicago Office.—The General Cable Corporation has moved its Chicago office from 20 North Wacker Drive to 111 North Canal St. The consolidation of office and warehouse provides complete facilities for the continuation of prompt service.

Trade Literature

Voltage Regulators.—Bulletin 1185A, 12 pp. Describes recent changes and developments in type BFR automatic branch feeder voltage regulators. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Fuse Links.—Bulletin 533A. Describes fuse links for plug type cutouts and cartridge type secondary fuses. W. N. Matthews Corporation, St. Louis, Mo.

Line Protection Equipment.—Cat. Sec. 5, 4 pp. Describes motor operated, automatic service restorers. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

Network Transformers.—Bulletin B2134, 20 pp. Describes application, construction and design of network transformers and other network equipment. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Pintype Insulators.—Bulletin 643-H, 6 pp. Gives catalog information on the complete line of O-B small pintypes, including the standard designs and the multi-ridge units known as Kingpins. Ohio Brass Co., Mansfield, Ohio.

Metal Clad Switchgear.—Bulletin 1145B, 16 pp. Describes horizontal, drawout, metal clad circuit breaker equipment for power stations, substations and general industrial purposes. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Reconditioning Equipment.—Bulletin GEA-2571B, 20 pp., "Reconditioning Flooded Electric Equipment." A detailed exposition of recommended methods for reconditioning water-immersed electrical apparatus. General Electric Co., Schenectady, N. Y.

Pyrometers—Bulletin 488, 12 pp. Describes millivoltmeter pyrometers. Types include: indicator controllers with enclosed mercury contacts or solid metal-to-metal contacts; single point indicators, and multiple-point indicators with rotary switch. The Bristol Co., Waterbury, Conn.

Wiring System.—Bulletin, 12 pp., "How to Mobilize Lighting and Power Outlets in Industrial Plants with Trol-E-Duct." Describes a flexible wiring system providing movable outlets. Applications in factory departments are illustrated. Bull Dog Electric Products Co., 7610 Jos. Campau Ave., Detroit, Mich.

Tap Switches.—Bulletin 381. Describes new developments in instrument type tap switches. This new line of switches covers both r.f. and low frequency applications. Standard units are available up to 60 amperes. All switches may be supplied with Mycalex insulation for use on the higher radio frequencies. Tech Laboratories, 7 Lincoln St., Jersey City, N. J.

Insulators.—Descrip. Data 39-180, 8 pp. Describes several types of high voltage pin type insulators including multipart design for average conditions, one piece high voltage insulators and bullet-proof types. Contains diagrams showing dimensions and construction; tables include wet and dry flashover, arcing distance, mechanical strength, etc. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Flexible Shafts—Bulletin 38, 28 pp. Describes flexible shafts for remote controls, applicable in operating from an accessible point, switches, valves and other electrical and mechanical controls located in remote or inaccessible positions. Shafts can be applied for either manual or automatic operation of controls; also, for operating any element requiring rotation or push-pull movement or both, with the controlled element close to or at a distance from the point of control; and for operating indicators of all kinds. Industrial Div., S. S. White Dental Mfg. Co., 10 East 40th St., New York.

Wood Pipes and Tanks.—Catalog "Wood Pipe Handbook," 275 pp., contains 150 illustrations. The subject matter ranges from an authoritative section on hydraulics to a description of the manufacture and application of wood pipe. A section is included in which problems encountered by engineers are solved both scientifically and through the use of flow tables prepared especially for this pocket size handbook. "Wood Tank Catalog" No. 37 describes tank installations of a wide variety. It shows how tanks and their foundations are designed and erected. Illustrations clarify many features of tank construction not usually published. National Tank & Pipe Co., Portland, Ore.

Highway Lighting.—Bulletin GEA-1097B, 8 pp. Illustrates and describes luminaires and accessory equipment, including discussion of arrangement and mounting height of units. The booklet further recognizes the significance of the different road surfaces, colors, and widths. The different G-E luminaires have various lighting characteristics, and sample charts show the performance of these luminaires in relation to unit height and street width. Line diagrams illustrate the construction of recommended mast arms and steel poles. Tables indicate prices of the different parts listed in the bulletin. General Electric Co., Schenectady, N. Y.

Instrument Transformers.—Bulletin B2138, 12 pp. Describes new instrument transformers providing reliable metering at low cost. The features covered are coordinated insulation, new wide-range accuracy on over-currents through type FW current transformers, potential transformers giving double protection against impulse voltage, quick-change construction of base and terminals to simplify changing current transformers to meet varying loads, and meter box which houses two FW current transformers with watthour meter and socket on cover. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Subway Oil Disconnects.—Bulletin 364, 8 pp. Describes type RA primary and type ARA secondary subway oil disconnects. The latter is a new addition to the G & W line of subway sectionalizing equipment. These boxes use floating contact rocker arm disconnecting links, gang operated by means of a handle on the outside of the box. The cables are sealed as they enter the box by means of individual porcelain insulated cable heads. The boxes provide a quick and easy means of switching secondary circuits and for isolating or interconnecting sections of cables. G & W Electric Specialty Co., 7780 Dante Ave., Chicago, Ill.

Line Material.—Bulletin 640-H, 36 pp., "O-B Materials for Distribution and Farm Lines." Describes pintype, suspension and porcelain insulators used for primary distribution circuits and farm lines; insulator fittings, etc., drawings are included which are typical of construction generally used to meet the demand for reliable low cost lines in rural territory; conductor tables; and data for designing such lines. Ohio Brass Co., Mansfield, Ohio.

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Type 713-B
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THE NEW Type 713-B Beat-Frequency Oscillator has a frequency range of 10 to 40,000 cycles. The extended upper limit is supplied for both general-purpose laboratory measurements and for the supersonic field.

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● ***WRITE FOR BULLETIN 280 FOR COMPLETE DATA***

GENERAL RADIO COMPANY

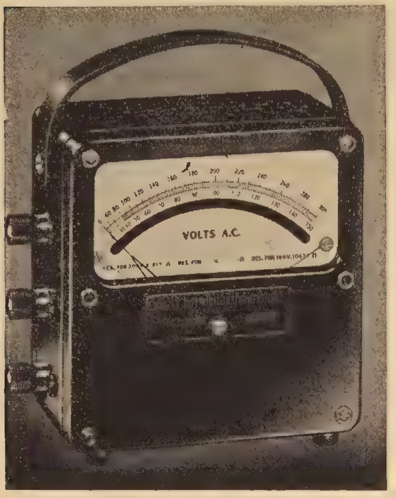
Cambridge, Massachusetts

BRANCHES: NEW YORK AND LOS ANGELES

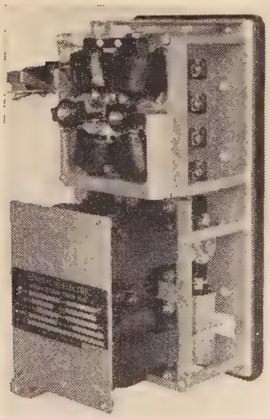
MANUFACTURERS of RADIO and ELECTRICAL LABORATORY APPARATUS

New Products

Voltmeters.—Portable, multi-range, model 433, a-c voltmeters with improved temperature compensation are now being offered by the Weston Electrical Instrument Corporation, Newark, N. J. The improvement will be of particular benefit in field test work by public utilities, where temperatures ranging from −20° to 120° F may be encountered. Instruments of the double range type (300/150 volts) and the triple range type (600/300/150 volts) are available with the improved compensation which holds temperature errors to 1% for 60°C (140°F) on both the 150-volt and 300-volt ranges and to 1% for 240°C (464°F) on the 600-volt range. Due to the special internal connections on these improved instruments, switches are used for range changing purposes, the switch for the double-range instrument being a double-pole, double-throw toggle switch and that for the triple-range type a double-pole, 3-position rotary switch.



Relay.—A new harmonic restraint current relay for use in bus differential protection has been announced by the General Electric Co. The new relay employs a principle of harmonic restraint to prevent it from operating because of current transformer transient unbalances. An operating element and a restraining element give this type HDC relay an identical construction to that of the fault detector of carrier-current protective apparatus. The operating circuit is tuned to pass fundamental line frequency and the restraining circuit is tuned to block fundamental frequency. As a result, the restraining current is composed of any harmonic currents present and the d-c component, if any.



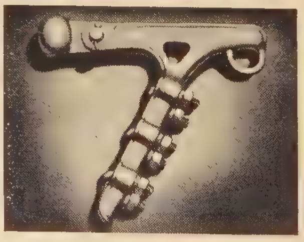
Overload Relay.—Struthers Dunn, Inc., 129 N. Juniper St., Philadelphia, Pa., announces a new overload relay available for use on either direct or alternating current. The contacts are rated 30 amperes at 110 volts a-c, 20 amperes at 220 volts a-c, 6 amperes at 110 volts d-c, and 3 amperes at 230 volts d-c on non-inductive loads. This relay is somewhat similar to the company's line of mechanical latch-in electrical reset relays. The contacts can be arranged to be closed manually or by means of a voltage operated coil. The latch is adjusted to pick up and open the contacts when the current in the overload coil reaches the proper value. This setting is adjustable by means of the knurled nut on the top of the relay over a range of 2 to 1.

Breakers House Metering Equipment.—A novel feature of 196–230 kv oil circuit breakers built by the Pacific Electric Manufacturing Company for installation by the City of Seattle (Wash.) at its Diablo hydroelectric generating station is the use of 12 bushing type current transformers arranged to serve the requirements of both metering and protective relays. Mounted two on each bushing, nine 1200/5 serve the relays, and three of the same ratio equipped with reactors serve the metering requirements. These breakers are reported to have been the first in which two bushing type current transformers per pole were used.

Running Time Meter.—R. W. Cramer & Co., Inc., 67 Irving Pl., New York City, announces a new running time meter which automatically registers the operating time of the circuit, apparatus or system to which it is connected. The meter, driven by a slow-speed self-starting synchronous motor, is made in two types—for registering total hours and total minutes. The device has a wide range of applications, including the recording of actual operating time of processing and production machines, x-ray and diathermy apparatus, blowers, welders, etc., and also for time study.

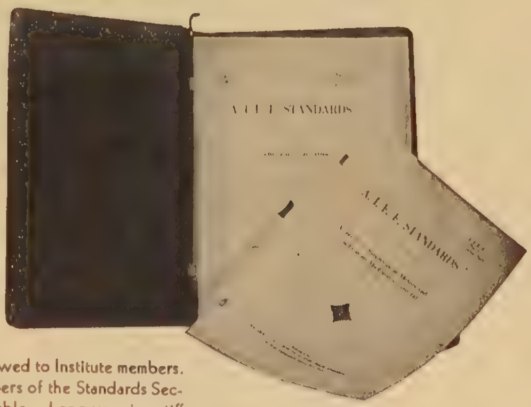
Auxiliary Breaker.—The Heinemann Electric Co., Trenton, N. J., announces a new auxiliary circuit breaker designed for the protection of fractional horsepower motors up to one horsepower and in ratings from 250 milliamperes to 35 amperes. A magnetic time delay unit takes care of harmless overloads while it opens instantaneously on heavy overloads and short circuits. Magnetic blowout contacts will withstand short circuits and reduce arcing to a minimum. All moving parts except handle are enclosed in a Bakelite case.

Looped Strain Clamp.—To simplify the job of dead-ending small conductors, the Ohio Brass Co., Mansfield, Ohio, has added a loop under the nose of its small Hi-Lite strain clamp, making it possible to attach the "blocks" for securing proper conductor tension directly in the clamp. When the tail block is hooked in the new loop and the conductor is brought to tension, the entire dead-end assembly assumes a position that is practically a continuation of the conductor. In addition to simplifying the procedure of dead-ending, the loop permits more accurate sagging and makes hot line work easier and safer.



A.I.E.E. STANDARDS

THE Standards of the American Institute of Electrical Engineers now comprise forty-seven sections on electrical machinery and apparatus. They are chiefly devoted to defining terms, conditions, and limits which characterize behavior, with special reference to acceptance tests, and many of them are recognized officially as American Standards.



The Standards available are listed below, together with prices. A discount of 50% is allowed to Institute members. Such discount is not applicable on extra copies unless ordered for other members. Numbers of the Standards Sections should be given when ordering. A binder (illustrated above) for standards is available. Long wearing stiff covers, resembling leather, lettered in gold. Price $1.75 net.

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*61	Specifications for Soft or Annealed Copper Wire. (Nos. 60 and 61 published as one pamphlet) (9-28)	.30
*C8.4	Specifications for 30 Per Cent Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
*C8.5	Specifications for Cotton Covered Round Copper Magnet Wire. (See C8.7 for price.)	
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*C8.7	Specifications for Enameled Round Copper Magnet Wire. (C8.5, 8.6 and 8.7 published as one pamphlet) (1936)	.30
*C8.11	Code Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
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No. 6	Mercury Arc Rectifiers.	40	Electrical Recording Instruments.
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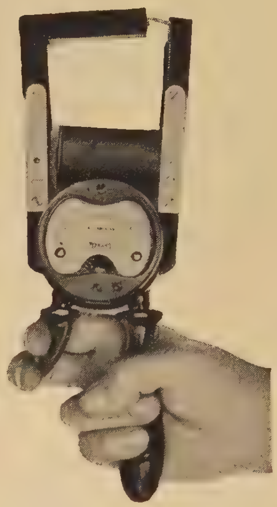

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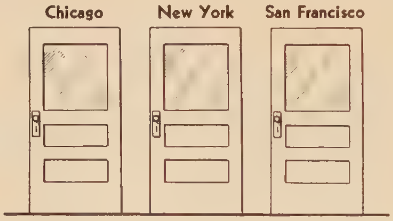

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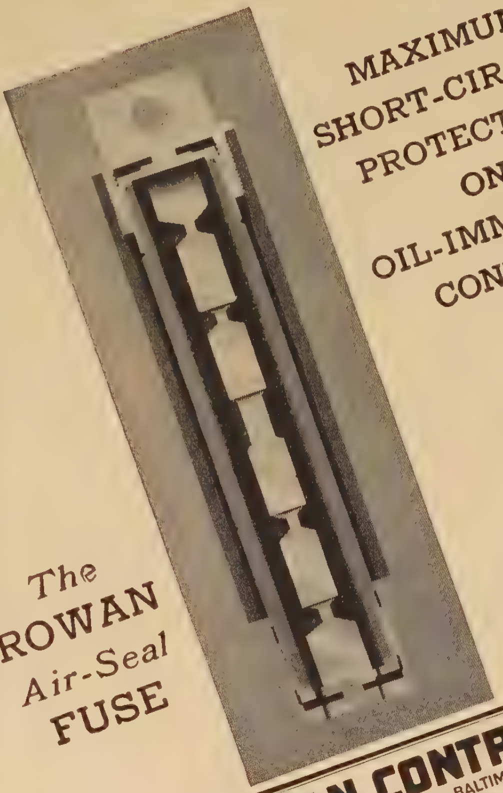

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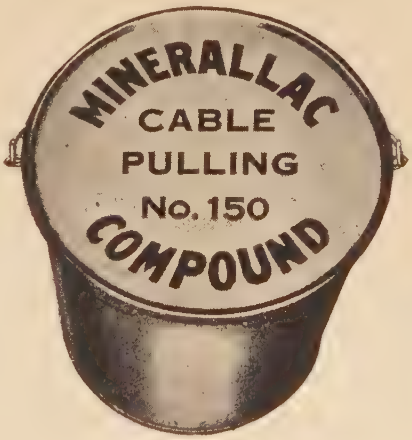

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Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

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B.S.E.E., 1931; 7 yrs elec planning and constr exper with util, mfr, city. Underground and vertical distr, underground cable, interior wiring, control eqpt, apparatus specification. Good exec and organizer. E-238.

ENGG CONSULTANT, nat reputation. Author, investigator, patentee, speaker. Interested in part time connection where exper, standing analytical and commercial ability, wide connections and skill in pub relations will be of value. E-227.

E.E., married; 7 yrs des, test, application fractional and integral hp motors; $2^1/_2$ yrs chief elec engr des of 180 cycle induction motors. Location immaterial. Registered engr. E-230.

E.E., 43, G.E. test, exper des and engg generating stations, substations, distr, indus plant, economic studies and acctg. Desires pos as engr with pub util or indus plant. Location immaterial. E-239.

GRAD E.E., 1931. Interested in engg draftg or maintenance engg; 3 yrs exper as plant electrician; $3^1/_2$ yrs exper in structural des, chem eqpt, pwr and ltg layout. Now employed. E-235.

EXEC ENGR; 30 yrs wide exper economic prod, plant utilization of steam and elec pwr. Util transm, distr. Available reasonable notice as plant or maintenance engr or as util exec. E-228.

B.S., E.E., G.E. test; interested in des and research; free hand drawing ability; Phi Kappa Phi Single, 24; location, East preferred. Much exper with induction motors. E-232.

E.E., '38. Specialized in com engg. Desires pos leading into des or eqpt engg. Available after June 1 upon grad from Clarkson Col of Tech. E-234.

E.E., '38, Clarkson. Specialized in heavy current and pwr engg. Desires pos leading into plant mgmt. Available after June 1 upon grad. E-236.

E.E., M.S., A & M Col of Texas, Feb 1938, single, 24; $1^1/_2$ yrs part time lab instructor. Desires work on research, devpmt or application of elec machy or transm. E-241.

E.E. AND METALLURGIST, 32, married, grad recognized col in elec engg; 6 yrs exper as oprtg engr, high voltage plant and elec arc furnaces, automatic regulations. Location immaterial. E-237.

REG ENGR, grad E.E., 13 yrs exper in pwr engg, pub util devpmt, reports, investigations, des; capable of quick adjustment to new duties; desires responsible connection. E-229.

LICENSED E.E., NY STATE, specialized com and photoelec problems, associate of Prof Pupin for 12 yrs, desires pos as research or elec. engr. E-233.

E.E. grad with 29 yrs exper in pub util field including 8 yrs on indus devpmt for large system desires pos in sales or mgmt. E-231.

Prof E.E., large Eastern Univ, author of books and papers. Has Doctor's and Master's degrees. Highly recommended for scholarship, character and teaching ability. E-240.

B.E.E., '32, exper in standardizing and testg with util; estimating for contractor and office engg in hydraulics. Desires pos testg, preferably high voltage, with util or mfr. E-242.

B.S., E.E., 1937, single; at present employed with pwr util. Exper testing high tension eqpt, swbd wiring, protective devices, outdoor substation constr, Carrier. Good knowledge radio. Desires pos foreign engg concern. E-243.

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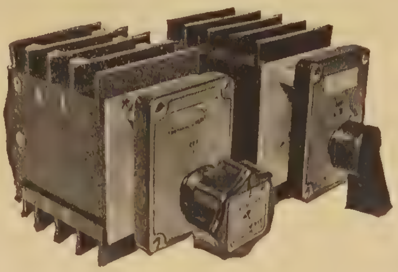

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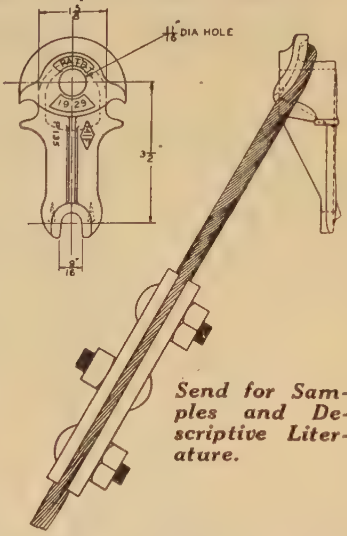

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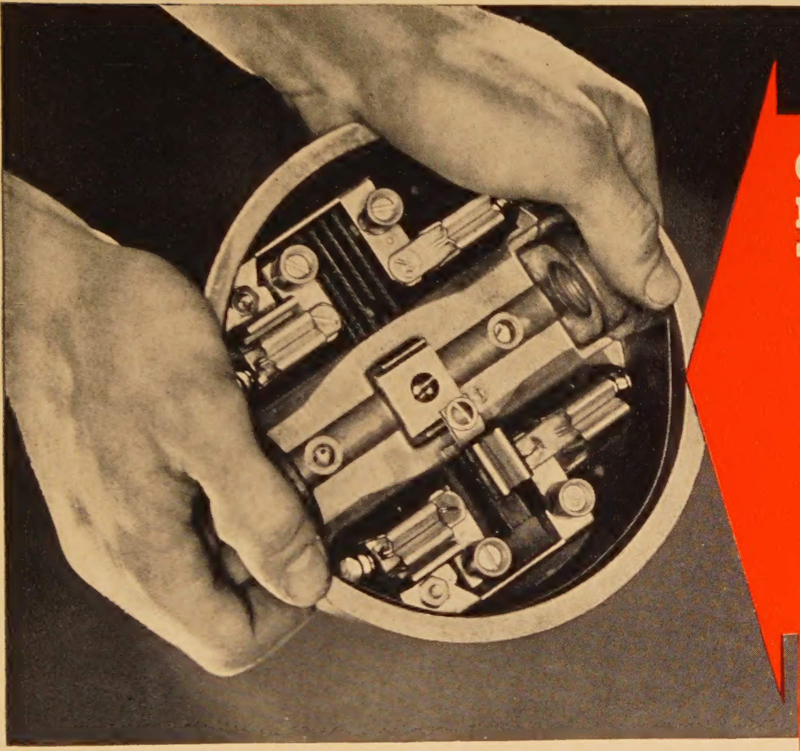

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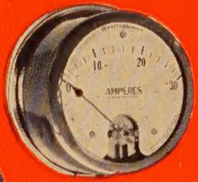

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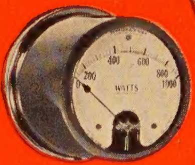

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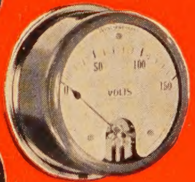

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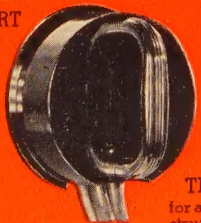

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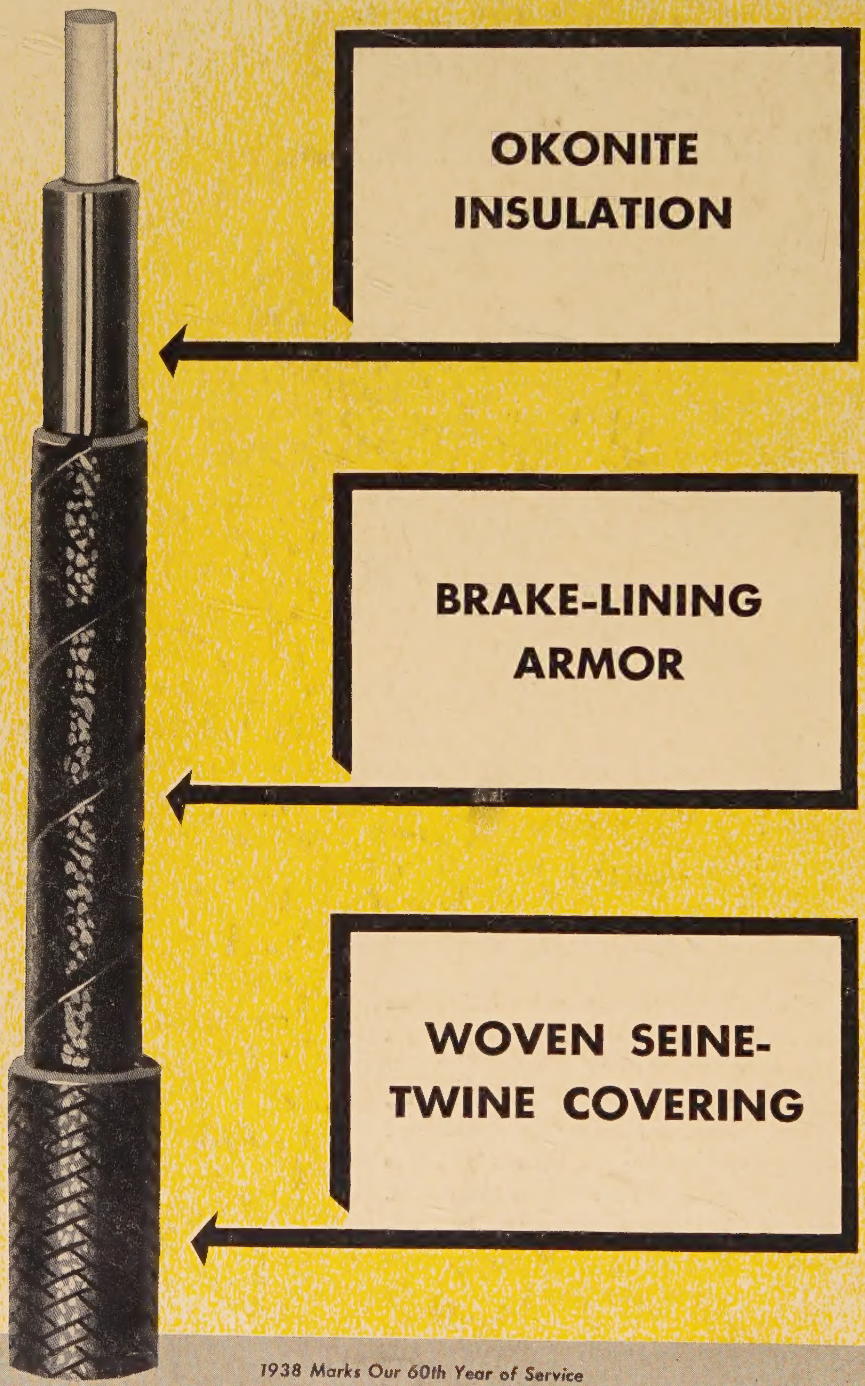

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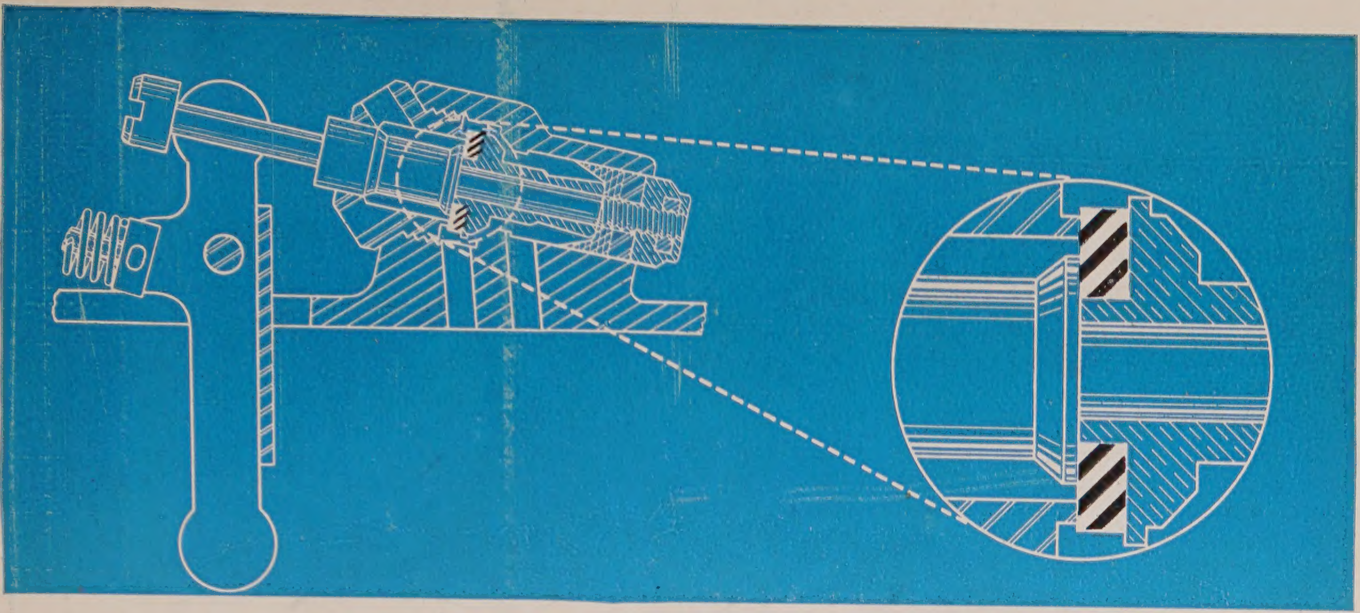

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Why Carpenter Nickel-Iron Alloys Give the Best Answer to the Low Expansion Problem

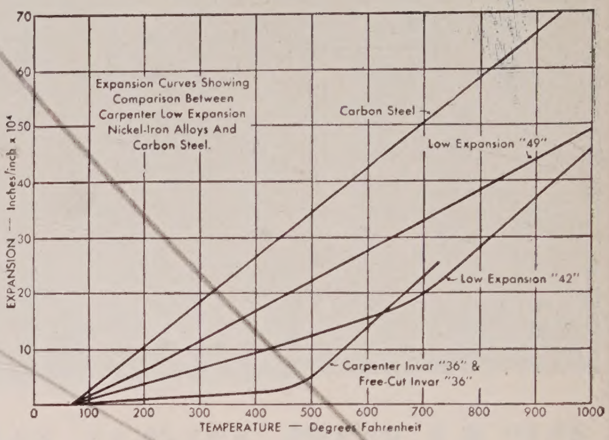
Patented Carpenter Free-Cut Invar "36" Simplifies Machining

For close control or dimensional accuracy of precision parts in devices where a low rate of thermal expansion is a must—Carpenter provides a group of Nickel-Iron alloys to meet this requirement over a wide range of temperatures.

The temperature range in which most applications fall is between room temperature and 400° F. A glance at the chart shows that this range is covered by Carpenter Invar "36". And the fact that this alloy is now also produced in a free-machining grade — Carpenter Free-Cut Invar "36"— greatly broadens its usefulness. For applications requiring a wider range of temperature, Carpenter Low Expansion "42" provides low thermal expansion characteristics up to 700° F. — and Carpenter Low Expansion "49" extends this range up to 1000° F.

Here, then, are alloys to meet practically any low thermal expansion problem that may come your way. And because of the great care Carpenter takes in making these alloys — melting within a closely controlled analysis range to insure constant uniformity from lot to lot—you can depend on them to give greater accuracy to thermostatic devices, radio equipment, electronic devices, precision scales, etc.

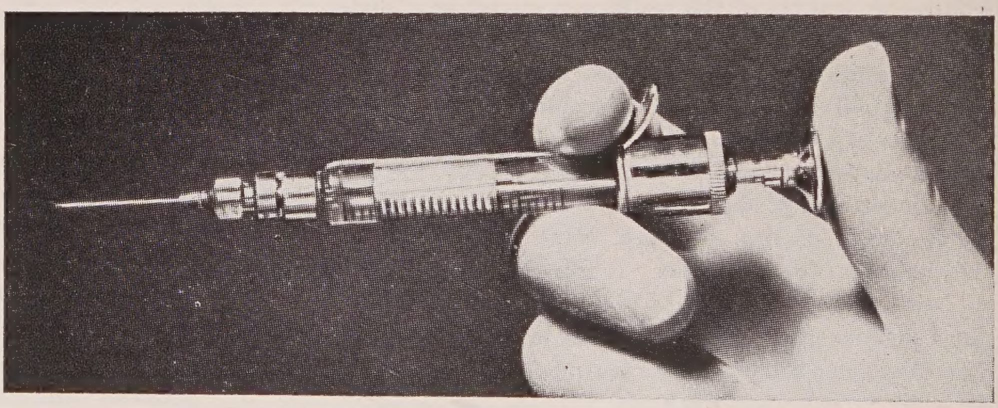
Let us help you apply these alloys to the solution of your design-engineering problems. Get in touch with us today.



⬆ Characteristics of Carpenter Low Expansion Alloys.

The plunger in this hypodermic syringe was made ⬇ from Carpenter Free-Cut Invar "36". The low thermal expansion properties of this alloy keep the plunger dimensions constant, even during sterilization in boiling water. And the alloy's free-machining qualities made it possible to produce the plunger to the necessary close tolerances for a flush fit in the glass cylinder, so essential in the operation of this instrument.

Ask For a Copy of our latest engineering bulletin on Carpenter Invar "36" and Free-Cut Invar "36". Our Metallurgical Department will be glad to supply information on the other alloys.



The Carpenter Steel Company, 120 W. Bern Street, Reading, Pa.

Carpenter
High Nickel Alloys

Temperature Compensator "30"
Carpenter Invar "36"
Carpenter Free-Cut Invar "36"
Glass Sealing "42"
High Permeability "49"